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HANDLING QUALITIES CRITERIA FOR THE SPACE SHUTTLE ORBITER DURING THE TERMINAL PHASE OF FLIGHT

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SYMBOLS

a_y	Lateral acceleration as sensed by an accelerometer
A_λ	Lead coefficient of λ numerator
b	Wing span
c	Mean aerodynamic chord
C_L	Lift coefficient
D	Drag
e	Napierian Base
g	Acceleration due to gravity
h	Altitude
H	Convergence altitude
I_x	Roll moment of inertia
I_{xz}	Product of inertia
I_z	Yaw moment of inertia
K	Gain
L	Lift
L	Sum of aerodynamic and thrust roll moments divided by roll moment of inertia
L_λ	$\partial L/\partial\lambda$ where $\lambda = \beta$, p, r, or δ
L_λ'	$\dfrac{L_\lambda + \dfrac{I_{xz}}{I_x} N_\lambda}{1 - I_{xz}^2/I_x I_z}$
M	Mach number
M	Sum of aerodynamic and thrust pitching moments divided by pitch moment in inertia
M_λ	$\partial M/\partial\lambda$ where $\lambda = u$, w, α, q, or δ

n_z	Normal load factor
n/α	Steady-state normal acceleration change per unit change in angle of attack for an incremental elevator deflection at constant speed
N	Sum of aerodynamic and thrust yaw moments divided by yaw moment of inertia
N_λ	$\partial N/\partial\lambda$ where $\lambda = \beta$, p, r, or δ
N'_λ	$\dfrac{N_\lambda + \dfrac{I_{xz}}{I_z} L_\lambda}{1 - \dfrac{I_{xz}^2}{I_x I_z}}$
N^λ_δ	Numerator of λ/δ transfer function
p	Roll rate
q	Pitch rate, $\dot{\theta}$
Q	Dynamic pressure
Q_o	Dynamic pressure for equilibrium flight at $(L/D)_{max}$
r	Yaw rate
s	Laplace operator
t	Time
T	Time constant
u	Velocity perturbation along x-axis
U_o	Steady state velocity along x-axis
v	Velocity perturbation along y-axis
V	Airspeed
V_o	Airspeed for equilibrium flight at $(L/D)_{max}$
w	Velocity perturbation along z-axis

W	Vehicle weight
W_o	Steady state velocity along z-axis
X	Sum of aerodynamic and thrust forces along x-axis divided by vehicle mass
X_λ	$\partial X/\partial\lambda$ where $\lambda = u, w, \alpha$, or δ
Y	Sum of aerodynamic and thrust forces along y-axis divided by vehicle mass
Y_{cf}	Aileron-to-rudder crossfeed transfer function
Y_p	Pilot transfer function
Y_λ	$\partial Y/\partial\lambda$ where $\lambda = \beta, v$, or δ
Z	Sum of aerodynamic and thrust forces along Z-axis divided by vehicle mass
Z_λ	$\partial Z/\partial\lambda$ where $\lambda = u, w, \alpha$, or δ
α	Angle of attack
β	Sideslip angle
$\Delta\beta_{max}$	Maximum sideslip excursion at the c.g., occurring within two seconds or one half-period of the dutch roll, whichever is greater, for a step aileron-control command
γ	Flight path angle
δ	Control deflection; specialized by subscripts: e for elevator, a for aileron, r for rudder
Δ	Characteristic determinant, denominator for transfer functions
ζ	Damping ratio of second-order mode
θ	Pitch attitude
μ	Crossfeed shaping parameter
σ_a	Longitudinal PIO parameter; $\sigma_a = \zeta_{sp}\omega_{sp} - (1/2)(1/T_{\theta_2})$
τ	Time delay

φ	Bank angle
φ_t	Bank angle change in t seconds for a step aileron-control command
$\lvert\varphi/\beta\rvert_d$	Roll/sideslip ratio in the dutch roll mode
ψ	Heading angle
ψ_β	Phase angle expressed as a lag for a cosine representation of the dutch roll oscillation in sideslip
ω	Undamped natural frequency of second-order mode
ω_c	Crossover frequency

Subscripts Used to Define Modes

d	Dutch roll pole
h	Altitude/elevator numerator zero
p	Phugoid pole
r	Yaw rate numerator zero
R	Roll subsidence pole
s	Spiral pole
sp	Short period pole
β	Sideslip numerator zero
θ	Pitch/elevator numerator zero
φ	Bank angle numerator zero

SECTION I

INTRODUCTION

This report is the result of a NASA-sponsored program to derive handling qualities criteria for the Orbiter part of the Space Shuttle Vehicle (SSV). The scope of this program was limited to the terminal phase of the Orbiter flight, i.e., altitudes less than 100,000 ft.

During this mission phase the Orbiter has much in common with conventional aircraft. Some of the required maneuvers, applicable piloting techniques, and handling quality problems are quite similar. Therefore a highly pertinent starting point for deriving handling qualities criteria is the latest military specification, Ref. 1. Much of the military specification is directly applicable. The objective of this program was to develop additional criteria for areas not covered by the military specification and substitute criteria for areas where the military specification is inadequate.

The overall project activities generally went as follows:

- Review of the military specification to define key problem areas for additional and modified criteria
- Pilot/vehicle analyses in these areas and correlations with existing handling qualities data
- Design and conduction of simulator experiments at NASA ARC to obtain additional data
- Additional analyses and data correlations to establish recommended criteria.

The simulator experiments noted above were of two different types. Some were parametric investigations of a particular problem area. The others were handling qualities evaluations of specific interim Orbiter designs. The specific vehicle tests provided an additional means of checking the criteria being developed.

The body of this report presents our recommendations for criteria to be used in addition to or instead of the military specification. It also describes the analytical and experimental evaluations of the specific

Orbiter designs. Details of the pilot/vehicle analyses, data correlations, and parametric simulation results are presented in the appendices.

The criteria recommendations are presented in Section II. The evaluations of three interim Orbiter designs are in Section III. Section IV is a brief summary with recommendations for areas which require additional research.

SECTION II

APPLICABILITY OF THE MILITARY HANDLING QUALITIES SPECIFICATION

As noted in the Introduction, the military handling qualities specification (8785B, Ref. 1) was used as a base point in this project. The purpose of this section is to present our recommendations for additions and revisions which should be made to 8785B for application to the SSV. These recommendations include several major modifications which are presented and discussed in Subsections A-E. There are also several rather minor modifications which do not require lengthy discussion. These are given in Subsection F.

A. FLIGHT-PATH STABILITY AND CONTROL

Paragraph 3.2.1.3 of 8785B restricts flight on the backside of the drag curve by limiting the value of $d\gamma/dV$. This criterion was developed for and should only be applied to aircraft which have thrust control. However, even for powered aircraft, there are indications that the 8785B requirement is deficient because of the significant interaction of other parameters with $d\gamma/dV$. Appendix A contains a detailed discussion of the problem and an analysis of some of the existing data, but a suitable revision cannot be recommended at this time. A thorough, detailed analysis of all the available data has not been completed and, even if it were, the existing data base appears to be inadequate. For the present, the retention of the 8785B requirement is recommended for powered orbiters.

For an unpowered orbiter new criteria are required. To establish these criteria we must consider the various phases in an unpowered approach and landing. It is generally agreed that unpowered SSV landings will be made in the manner indicated in Fig. 1. The initial approach is made at essentially a constant flight path angle and equivalent airspeed. The vehicle is aimed at a point short of the runway. The next phase is the initial flare during which the flight path is shallowed to an angle on the order of 3 deg. During the ensuing float phase the vehicle is again flown at a constant flight path angle while the airspeed decreases. After

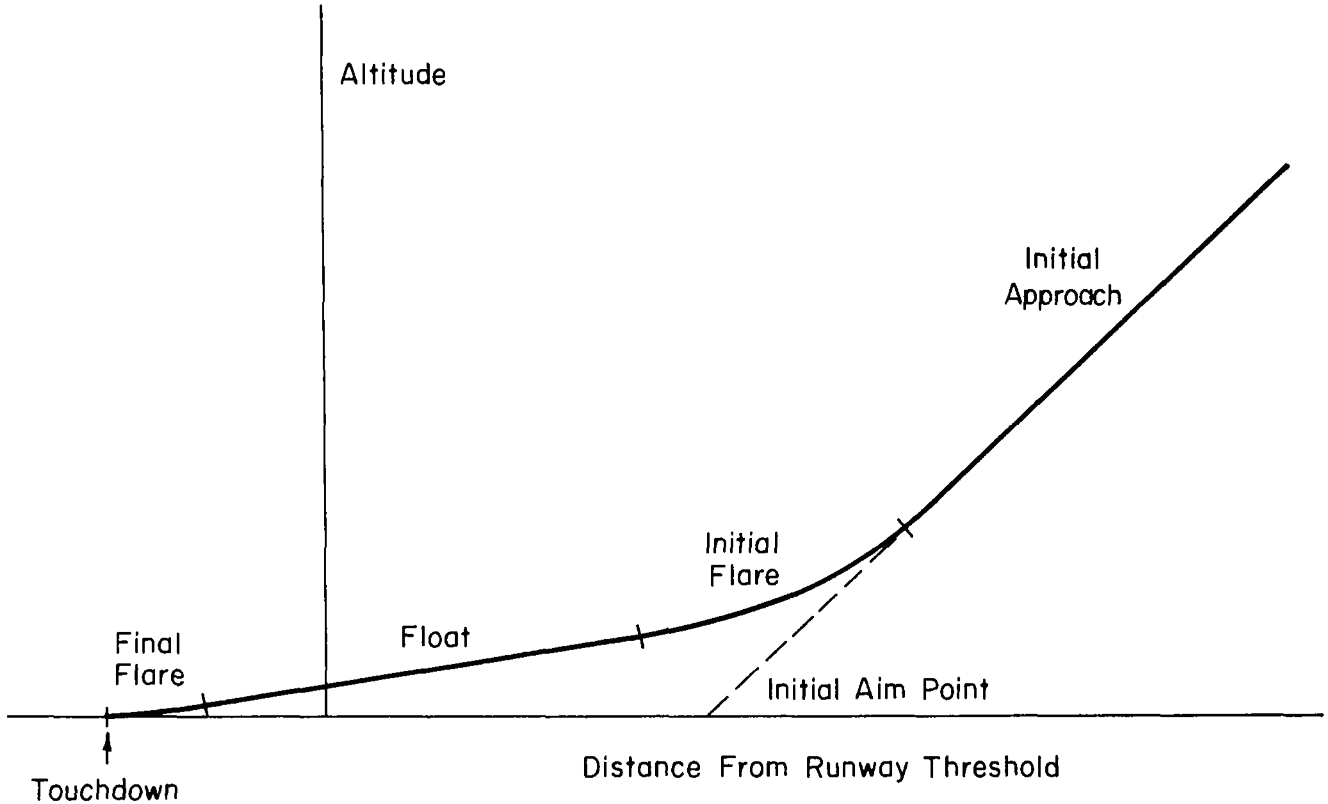

Figure 1. Unpowered Approach and Landing Trajectory

crossing the runway threshold a final flare is made to arrest the rate of descent.

One of our first concerns was the handling qualities criteria for the initial approach phase. This phase should be made on the frontside of the drag curve (i.e., at speeds greater than that for maximum L/D) to preserve normal piloting technique, which involves pitch up to reduce flight path angle. The problem was to define how far on the frontside was necessary. A number of parameters which might be critical were derived, but examination of numerical values from several flight test experiments failed to indicate the critical limiting value for these parameters. Therefore a simulation experiment was conducted at ARC.

This experiment was designed to isolate the most critical parameter and find the limiting value. However, this experiment showed no handling quality problems per se as long as the approach was on the frontside of the drag curve. The only problems were of a performance nature — whether or not the pilot had sufficient maneuver capability to compensate for initial errors. Thus from a handling qualities viewpoint it is only necessary to be on the frontside ($d\gamma/dV < 0$) and the real limits on the initial approach will be set by performance considerations. Enough maneuver capability must be provided so the pilot can compensate for possible initial errors and wind variations. These performance requirements will define how far on the frontside the nominal approach should be.

Details of the analysis and simulation experiment are given in Appendix B.

As part of a later simulation (reported in Appendix C) we did find that pilots objected if the initial approach was too steep. From those results we concluded that the angle of descent should be limited to less than 20 deg for the SSV.

The simulation experiments described in Appendix C concentrated on longitudinal control problems during the initial flare, float, final flare, and touchdown phases. Based on these results and earlier data, the key requirements during these phases are:

- $1/T_{\theta_2}$ (higher frequency zero of pitch/elevator transfer function) greater than 0.4 sec^{-1} before the Orbiter crosses the runway threshold

- Float time (from completion of initial flare to the runway threshold) greater than six times the value of T_{θ_2} at the threshold.

The requirement for being on the frontside ($d\gamma/dV < 0$) during initial approach should be eliminated for these later phases. It was shown that landings well on the backside can be easily accomplished.

It should be noted that the above recommendations are based primarily on the simulation experiments reported in Appendix C. In these tests the float phase and landing was done VFR, but the cockpit display also included raw ILS data. The limiting values of $1/T_{\theta_2}$ and float time may change for different display conditions. The requirements for IFR may be more stringent; and use of a flight director display might ease the requirements. There were also some indications of a possible effect of L/D on the criteria; however, the effect cannot be defined from the current data.

B. PITCH ATTITUDE CONTROL

A fundamental problem with 8785B is that it only restricts two dynamic modes, the short period and the phugoid. For an unaugmented aircraft, limiting the short period and phugoid modes can be adequate as these are the only dynamic modes. For an augmented aircraft this approach is not satisfactory as the augmentation system may introduce several additional modes. These additional modes can drastically alter the longitudinal responses of the aircraft so that the apparent short period characteristics, as seen by the pilot, are substantially different from the actual short period characteristics. Two examples of this effect are given in Ref. 2.

To correct this problem all short period requirements should be specified in terms of the "equivalent" short period. The equivalent short period characteristics are defined by matching the aircraft pitch controller/pitch attitude responses with a simple model — the conventional short period approximation. The matching can be done in the time domain or the frequency domain (matching over the frequency range of concern to the pilot in controlling pitch). With this modification the specification would then limit the response characteristics seen by the pilot.

A modification to the 8785B requirements for final approach and landing (Category C in 8785B) is also recommended. The modification was derived in an Air Force sponsored program of which Ref. 2 is the final report. The background data and rationale for the modification are given in Ref. 2. However, the modification given below is the "original" one developed in that program, not the simplified version contained in the final report. A comparison of both versions with data obtained in this project indicated that the original version was more appropriate here.

The proposed requirements* for the equivalent short period are:

- $\omega_{sp}^2/(n/\alpha)$ less than 3.6 for Level 1 and less than 10 for Level 2 (same requirement as 8785B)

- ζ_{sp} greater than 0.35 for Level 1, 0.25 for Level 2, and 0.15 for Level 3 (same requirement as 8785B)

- ω_{sp} and $2\zeta_{sp}\omega_{sp}$ greater than the limits given in Figs. 2 and 3.

Our simulation experiences during this project also showed the importance of the longitudinal trim system. The series trim system used on the side-arm controller was found to have a dominant negative effect on the pilot ratings during the initial longitudinal control experiments. The primary problems with the system were:

- It was possible to forget to trim because of the light longitudinal spring forces on the side-arm controller. This resulted in running out of elevator just prior to final flare and touchdown. (Full controller deflection in the pitch direction typically produced only 50% of total elevator travel; trimming shifted the elevator deflection for neutral controller.)

- Because of the series type trimmer, it was necessary to manually recenter the stick while trimming. This required a good deal of trim to stick coordination to avoid longitudinal oscillations. It is believed that configurations with low short period damping received unreasonably poor pilot ratings because of this problem (see Appendix C).

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*The levels indicated here are the same as those in 8785B.

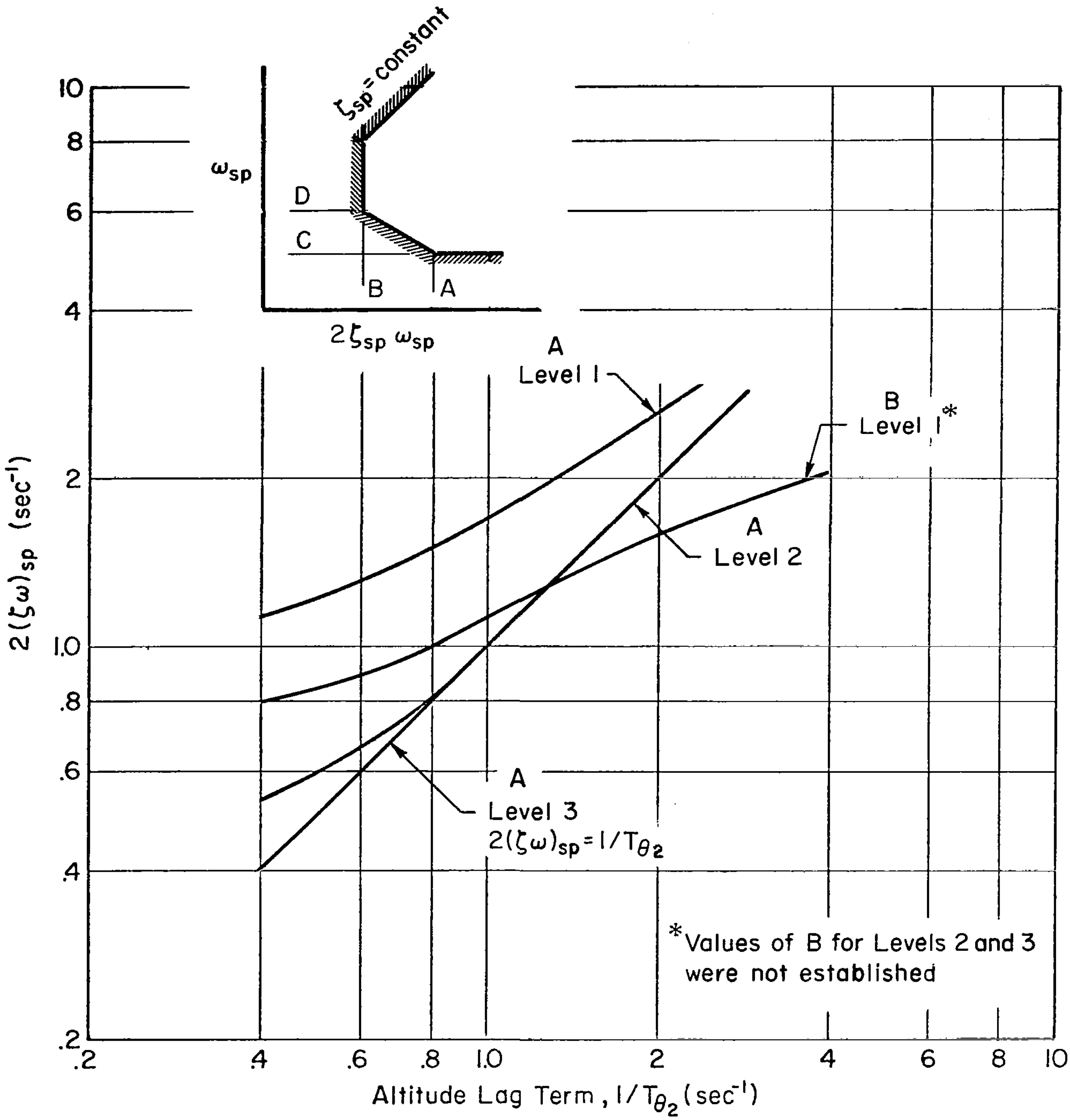

Figure 2. Minimum Short Period Damping

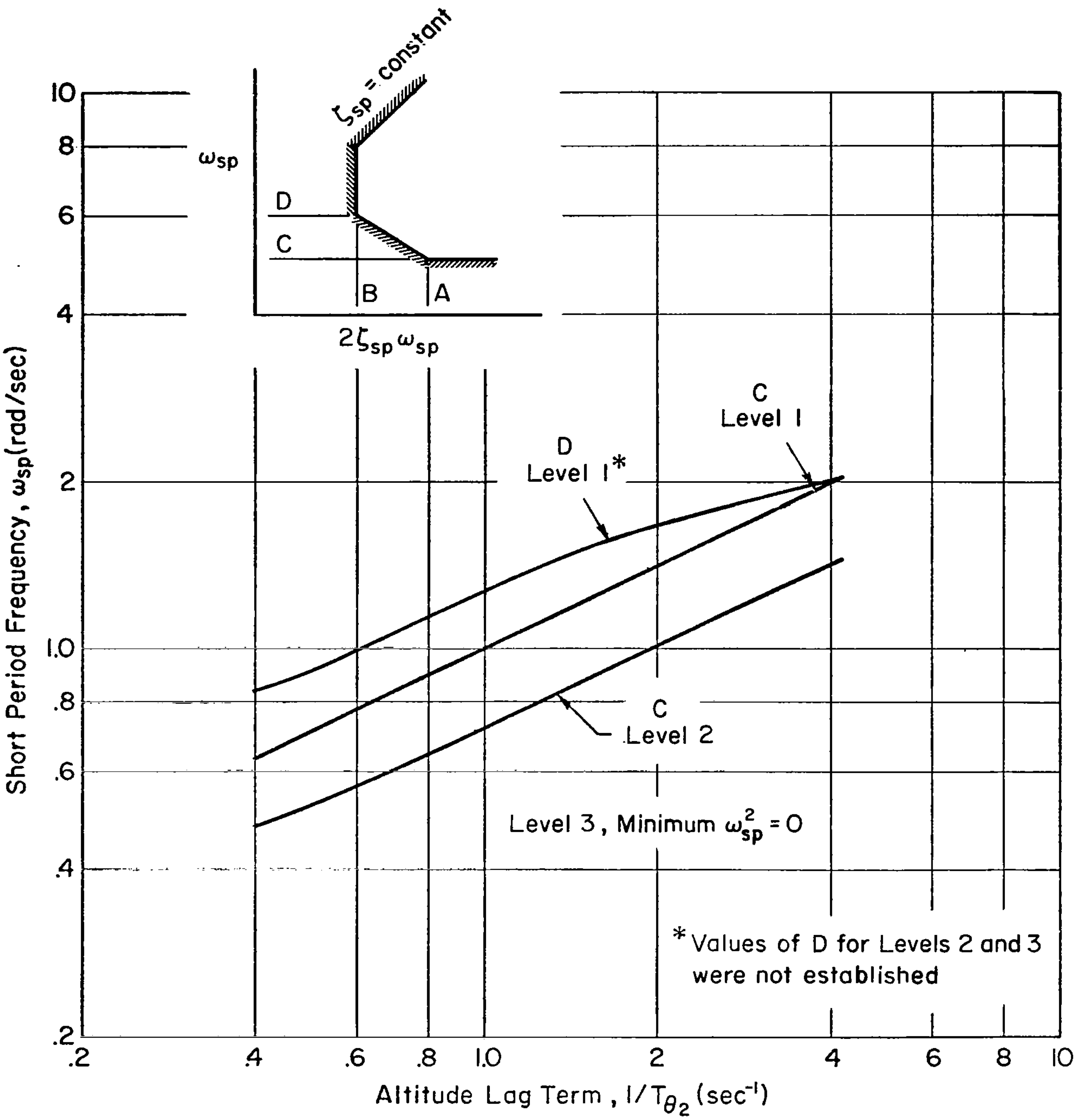

Figure 3. Minimum Short-Period Frequency

- For many configurations it was difficult to impossible to get full required elevator and still maintain the trim sensitivity at a reasonably low value. This problem could probably be alleviated by using a two turn pot on the trim wheel.

Although a complete evaluation of the trim problem was beyond the scope of the present work, several possible solutions were briefly considered. One possibility would be to use the more conventional parallel trim arrangement where the pilot simply trims out the stick force without having to recenter the stick to neutral. The drawback to this system is that the limited travel of a side-arm controller will probably result in unacceptably high stick sensitivity (full stick equals full elevator in a parallel system). The most obvious fix would then be to schedule the maximum elevator travel or stick sensitivity with speed or dynamic pressure. An alternative and more simple solution would be to use a center stick controller. The increased travel of this type controller results in lower stick sensitivity and would allow use of a parallel trim system without modification of the elevator limits.

Shuttle trajectories have been flown in various aircraft using a center stick or wheel with parallel rate trim. Results of those experiments indicated that trimming the aircraft over the complete speed range was not a problem. Finally, it is possible to eliminate the trim problem completely by going to a rate command attitude hold system. This alternative was used in the present experiments as discussed in Appendix C.

Based on the experience obtained during the present work, it appears that the following need to be investigated before a comprehensive specification can be made for side-arm controllers.

- Increased spring force on side-arm controller to provide better trim cues
- Trim wheel (position) versus trim rate "beeper"
- Parallel trim on side-arm controller with stick sensitivity programmed as a function of dynamic pressure.

C. LONGITUDINAL PILOT-INDUCED OSCILLATIONS

Paragraph 3.2.2.3 of 8785B merely prohibits pilot-induced oscillations (PIO's) without providing any quantitative guidance to the control system designer. A PIO criterion was developed in Ref. 2, and we recommend including it in a SSV specification. The proposed limitations on control system phase lag as a function of the equivalent short period characteristics are given in Fig. 4.*

This criterion applies only for tasks which require tight attitude control (see Ref. 3). Furthermore, the $\sigma_a = 0.5$ boundary is not well defined because of a scarcity of data in this region and the possible effects of controller characteristics.

D. HEADING CONTROL

The military handling qualities specification has no criteria on heading control per se. It attempts to insure adequate heading control by restricting the amount of sideslip in aileron-alone turns. While small sideslip will provide good heading control, the general validity of such an indirect criterion is questionable. In fact, recent data have shown that the criterion is deficient (see Appendix D for additional details).

Because of these problems and the importance of adequate heading control in the final approach, a substantial portion of this project was devoted to developing a better heading control criterion. These efforts are detailed in Appendix D, and only the recommended criterion is discussed below.

The recommended criterion is based on the aileron-to-rudder crossfeed which would be required to coordinate turns, i.e., keep sideslip equal to zero. The criterion involves two parameters. One is the ratio of aileron yaw to roll acceleration, $N'_{\delta_a}/L'_{\delta_a}$, measured in stability axes, divided by dutch roll frequency squared. The second parameter, μ, defines the shape of the required crossfeed. This parameter is computed as follows:

- Compute the ideal rudder/aileron crossfeed, Y_{cf}, required to keep zero sideslip. This computation

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*The levels indicated in the figure are the same as those in 8785B.

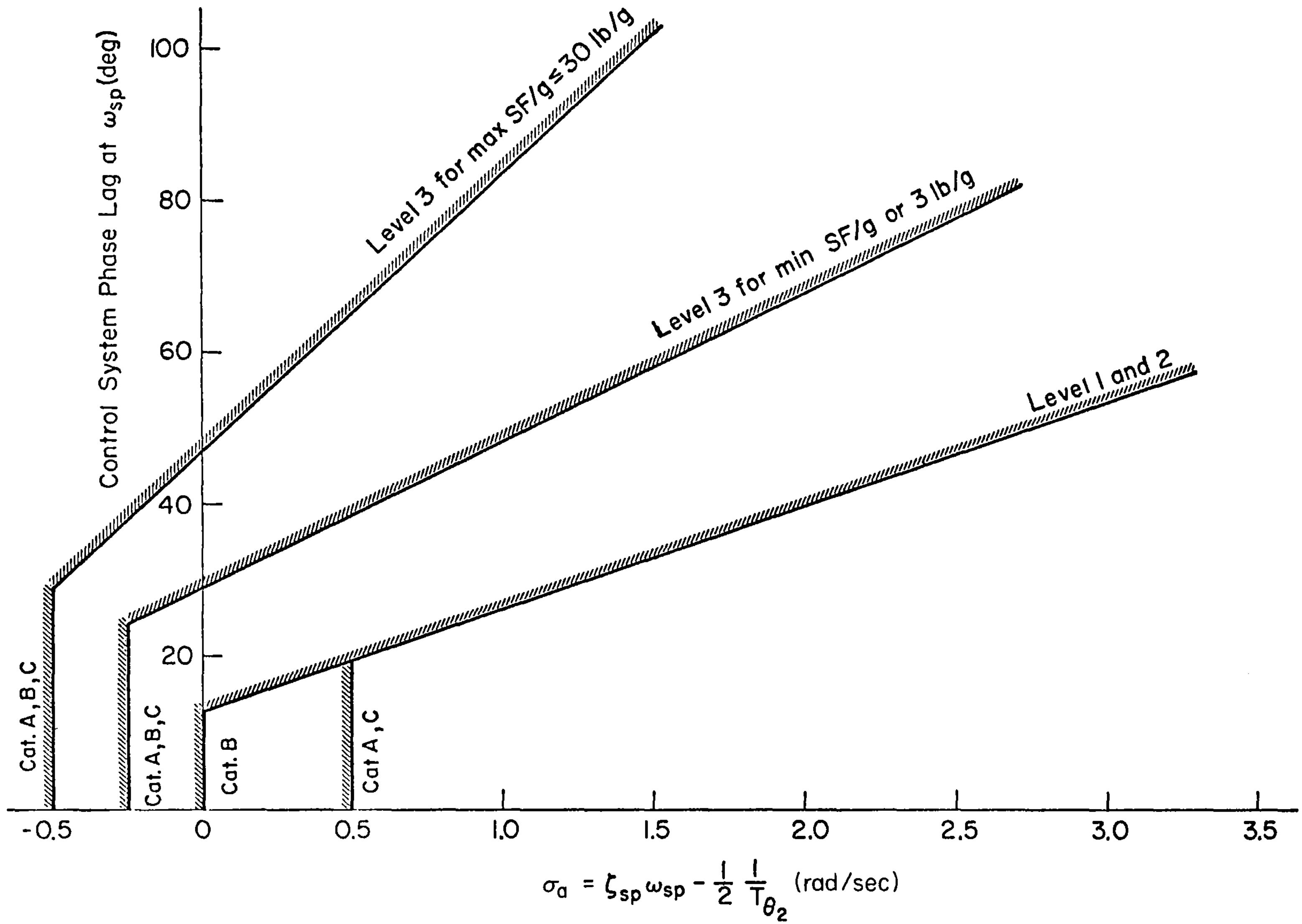


Figure 4. Requirements for Avoidance of Pilot-Induced Oscillations

can be based on the measured or estimated sideslip/stick and sideslip/rudder pedal frequency responses, i.e.,

$$Y_{cf} = -\frac{\text{sideslip/stick frequency response}}{\text{sideslip/rudder pedal frequency response}}$$

where the frequency responses are those of the airplane plus appropriate augmentation systems.

- Over the frequency range 0.2-5 rad/sec, approximate the ideal crossfeed by a filter of the form

$$\frac{-N'_{\delta_a}}{N'_{\delta_r}} \frac{(s + z)}{(s + p)}$$

- μ is given by

$$\mu = \frac{z}{p} - 1$$

The value of μ and $N'_{\delta_a}/L'_{\delta_a}\omega_d^2$ should then fall within the contours shown in Fig. 5 for Level 1 (as defined in Ref. 1) flying qualities.

It was found that the above was not appropriate if the magnitude of aileron-yaw became quite small. Then the yaw due to roll rate is the critical parameter. It is therefore recommended that if $|N'_{\delta_a}/L'_{\delta_a}| \leq 0.04$, the following be used instead of Fig. 5 (N'_p also measured in stability axes):

$$-0.25 < N'_p - \frac{g}{U_o} < 0.15 \text{ sec}^{-1}$$

As a final point on heading control a design problem encountered in our simulation experiments will be described (see Appendix D for additional details). In a large aircraft approaching at high angles of attack the pilot can be situated several feet above the stability axes. If the aircraft is coordinated it will roll about the velocity vector or stability X axis. This can produce highly objectionable side accelerations at the cockpit, especially if the aileron roll acceleration is high. The only solutions are to reduce the aileron power below what is normally considered desirable or to degrade the degree of coordination. Both have deleterious effects so a design compormise must be made. The outcome of the proper compromises needs further investigation and definition.

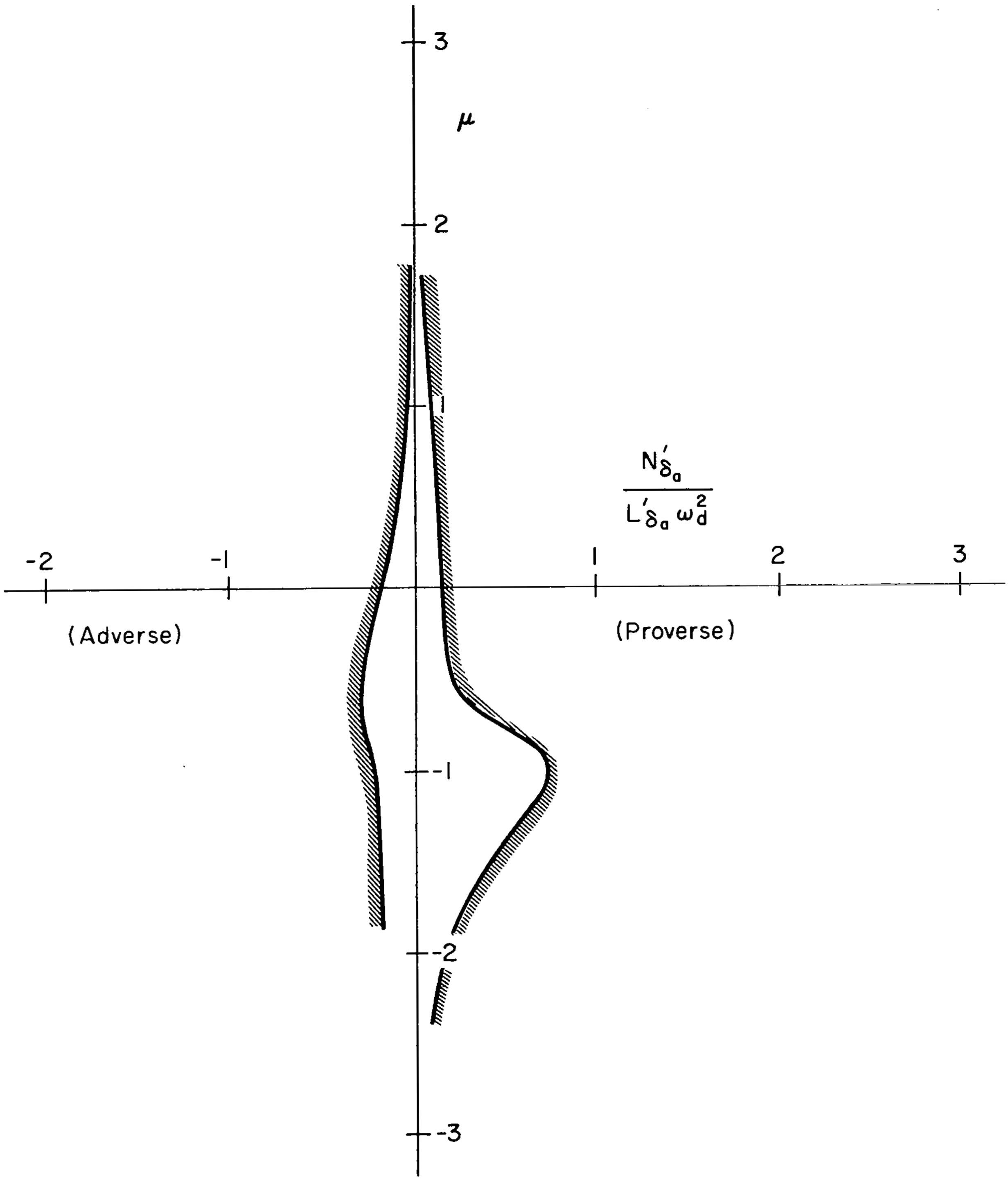


Figure 5. Recommended Heading Control Criterion for $|N\delta_a'/L\delta_a'| > 0.04$

E. PRIMARY FLIGHT CONTROL SYSTEM DYNAMICS

Paragraph 3.5.3 of 8785B specifies the allowable lags from cockpit control force inputs to control surface motions. This particular item is deficient in at least two aspects. First of all, it effectively prohibits the use of stick filters for the high short-period frequency, low $1/T_{\theta_2}$ situations. A stick filter has been found to be very desirable in these cases, but is prohibited by this paragraph. The stick filter replaces the lag equalization the pilot would otherwise have to adopt. Without the stick filter the pilot will complain of excessive aircraft sensitivity and an annoying tendency to bobble.

The second deficiency of this paragraph is that it permits excessively large control system lags when the short-period frequency or the dutch roll frequency and $1/T_R$ are low. For example, the stick to elevator response could have a first-order lag at $1.7\ \omega_{sp}$ or a second-order lag at a frequency of $2\ \omega_{sp}$ and a damping ratio of 0.5. For the very low short-period frequency situations these lags would be completely unacceptable. The low frequency phase lags would most seriously degrade the pilot's control of pitch attitude.

It is therefore recommended that Paragraph 3.5.3 of 8785B be replaced by the criterion developed in Ref. 2. The requirement is that the total phase lag from cockpit control force or displacement to vehicle attitude at a frequency of 1 rad/sec be less than 135 deg for Levels 1 and 2, and less than 180 deg for Level 3. This requirement applies to:

Control	Angle
Elevator	Pitch
Aileron	Roll
Rudder	Yaw

F. MISCELLANEOUS TOPICS

There are numerous other parts of 8785B which should be changed before it is applied to the SSV. Some of these are obviously not applicable (e.g., defining various classes of aircraft) and deserve no further comment.

A general problem is that 8785B does not consider the use of a side-arm controller. Modifications should be made to allow for such a controller.

Finally, there are a series of recommended revisions and unresolved problems which are listed below:

1. Only two Flight Phase Categories (equivalent to Categories B and C of 8785B) should be necessary.

2. Only two Levels of Flying Qualities should be necessary; and these should correspond to Levels 1 and 3 of 8785B. Probabilities of encounter (Paragraph 3.1.10.2) should be adjusted accordingly.

3. Paragraph 3.3.2.5 limits rudder pedal forces for zero sideslip in rolls. Zero sideslip is overly restrictive — should limit rudder pedal forces to keep sideslip less than some finite value.

4. Paragraph 3.3.7.1, Final Approach in Crosswinds, does not insure adequate rudder power to rapidly decrab. If aircraft directional stability is low, the 8785B requirement to develop at least 10 deg of steady sideslip could be met with relatively low rudder power.

5. Paragraphs 3.5.5.1, Failure Transients, and 3.5.6.1, Transients, should be modified per the recommendations in Ref. 2, quoted below:

3.5.5.1 Failure transients. With controls free, the airplane motions due to failures described in 3.5.5 shall not exceed the following limits for at least 2 seconds following the failure, as a function of the Level of flying qualities after the failure transient has subsided: (no change)

Levels 1 and 2 (after failure)	±0.5g normal or lateral acceleration at the pilot's station, except that lateral acceleration shall not exceed structural limits nor shall vertical or lateral excursions exceed 5 ft; and ±10 degrees per second roll and ±2 degrees bank angle
Level 3 (after failure)	No dangerous attitude or structural limit is reached, and no dangerous alteration of the flight path results from which recovery is impossible (no change)

3.5.6.1 Transients. With controls free, the transients resulting from the situations described in 3.5.6 shall not exceed the following limits for at least 2 seconds following the transfer:

Within the Operational Flight Envelope	±0.1g normal or lateral acceleration at the pilot's station and ±3 degree per second roll
Within the Service Flight Envelope	±0.5g at the pilot's station, ±5 degrees per second roll, and the lesser of ±5 degrees sideslip or the structural limit (no change)

These requirements apply only for Airplane Normal States.

SECTION III

HANDLING QUALITIES EVALUATION OF THREE SPECIFIC VEHICLES

Three proposed shuttle configurations were briefly evaluated. The evaluation procedure consisted of an initial analytical study to isolate potential problem areas followed by an experimental evaluation on the NASA S-16 Simulator (see Appendix E for details of the simulation). The shuttle configurations analyzed were:

- McDonnell Douglas Low Cross Range (MDAC-2 LCR)
- North American High Cross Range (NAR HCR 134C)
- McDonnell Douglas High Cross Range (MDAC HCR)

The results of the analytical and experimental evaluations are given in the following.

A. ANALYTICAL HANDLING QUALITIES SURVEY FOR MDAC-2 LCR

The handling qualities of the MDAC-2 LCR, Fig. 6, were analyzed at two specific flight conditions. These flight conditions were based on guidance trajectories published in Ref. 4 and were chosen to represent the nominal glide and a glide at maximum L/D. The latter case involves prolonged flight at a fairly high angle of attack and minimum dynamic pressure, both of which tend to degrade the vehicle handling qualities. The lateral characteristics in a third flight condition, during the flare, were also examined. The longitudinal characteristics were similar to those of the first two flight conditions. The three flight conditions are summarized in Fig. 7.

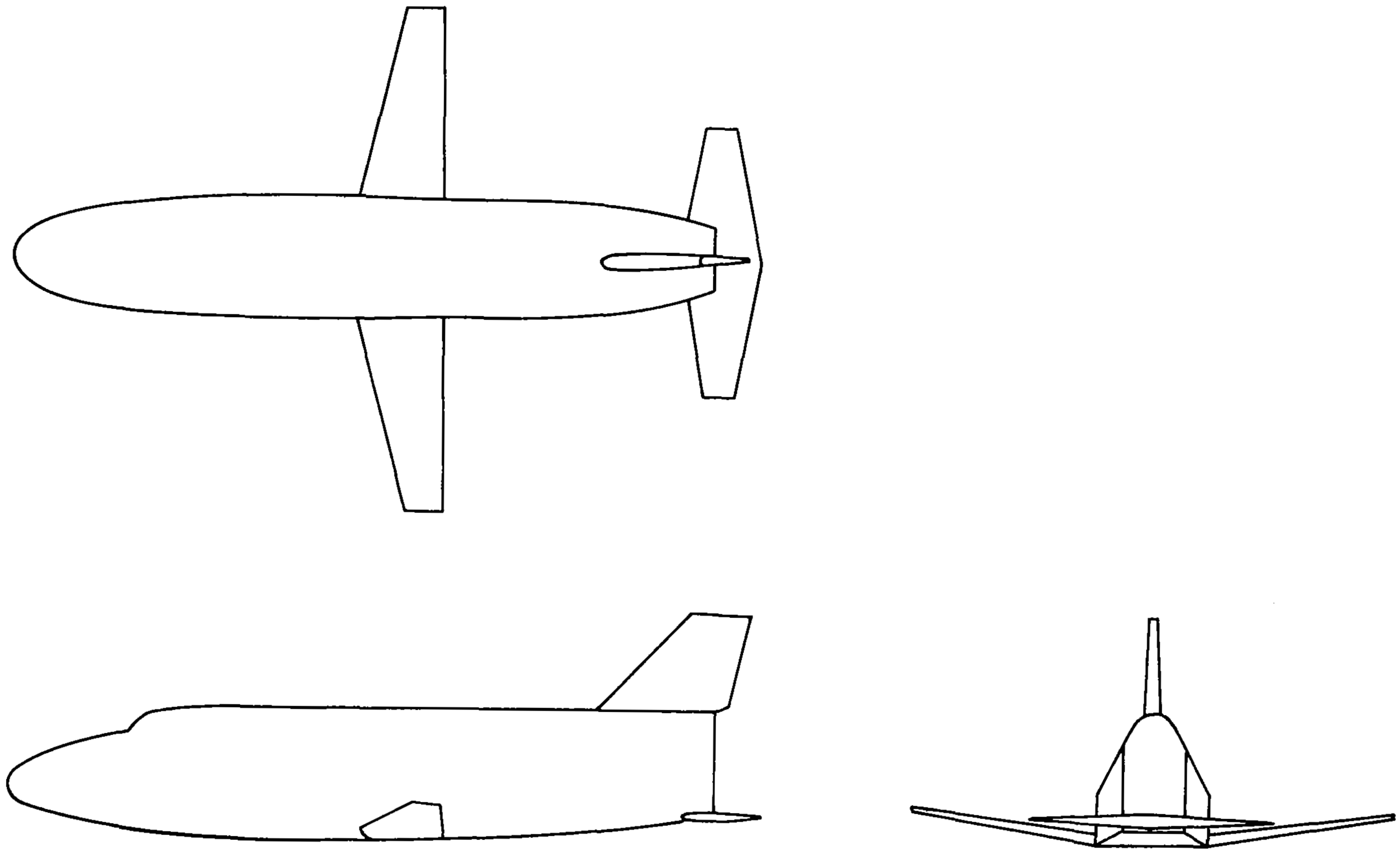
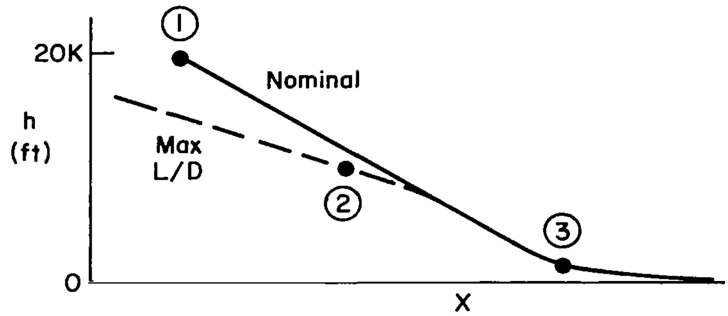


Figure 6. MDAC-2 LCR Configuration



FLIGHT COND.	h ft	V kt	M	Q PSF	C_L	α deg	REMARKS
1	20,000	369	0.6	247	0.45	2.25	γ_0 = −12 deg nominal glide
2	10,000	252	0.4	160	0.70	6.0	γ_0 = −10 deg max L/D, low Q
3	625	268	0.41	240	0.90	8.8	2g flare maneuver

Figure 7. Summary of Selected Flight Conditions, MDAC-2 LCR

The stability derivatives and key transfer functions are listed in Table 1 .

A summary of some pertinent longitudinal handling quality factors for Flight Conditions 1 and 2 are given in Table 2 and Fig. 8. Figure 8 indicates that the short-period frequency may be marginal. Table 2 also indicates that the parameter σ_a does not meet the PIO criterion of Section II-C. While neither deficiency presents a severe problem, the longitudinal characteristics should be at best marginally satisfactory.

TABLE 1-a

DIMENSIONAL DERIVATIVES FOR MDAC-2 LCR

DERIVATIVES ARE IN FUSELAGE REFERENCE AXES

		FLIGHT CONDITION 1	FLIGHT CONDITION 2	FLIGHT CONDITION 3
h	ft	20,000	10,000	625
V	ft/sec	623	426	454
α	deg	2.25	6.0	8.8
W	lbs	210,000	210,000	210,000
X_u	sec^{-1}	−0.018	−0.018	−0.0042
X_w	sec^{-1}	0.013	0.055	−0.122
Z_u	sec^{-1}	−0.081	−0.106	−0.197
Z_w	sec^{-1}	−0.611	−0.591	−0.628
$Z_{\dot{w}}$		−0.0066	−0.0091	−0.012
M_u	rad/ft sec	0.00015	0.000077	−0.00003
M_α	sec^{-2}	−0.588	−0.313	−0.584
$M_{\dot{\alpha}}$	sec^{-1}	−0.117	−0.109	−0.153
M_q	sec^{-1}	−0.440	−0.415	−0.607
X_{δ_e}	$ft/sec^2/rad$	8.99	6.35	8.96
Z_{δ_e}	$ft/sec^2/rad$	−61.80	−47.80	−59.80
M_{δ_e}	sec^{-2}	−1.99	−1.36	−1.94
Y_β	$ft/sec^2/rad$	−171.8	−114.1	−172.2
L'_β	sec^{-2}	−1.34	−1.077	−1.63
N'_β	sec^{-2}	0.484	0.327	0.457
L'_p	sec^{-1}	−1.15	−1.07	−1.44
N'_p	sec^{-1}	0.0139	0.0046	0.0024
L'_r	sec^{-1}	0.914	1.04	1.73
N'_r	sec^{-1}	−0.216	−0.222	−0.339
Y_{δ_a}	$ft/sec^2/rad$	−4.08	−2.64	−1.00
L'_{δ_a}	sec^{-2}	3.83	2.15	1.62
N'_{δ_a}	sec^{-2}	0.012	0.0083	−0.076
Y_{δ_r}	$ft/sec^2/rad$	25.4	16.4	24.78
L'_{δ_r}	sec^{-2}	1.67	1.08	1.63
N'_{δ_r}	sec^{-2}	−0.708	−0.434	−0.655

TABLE 1-b

SELECTED LONGITUDINAL TRANSFER FUNCTIONS FOR MDAC-2 LCR

	FLIGHT CONDITION		1	2
	h	ft	20,000	10,000
	V	ft/sec	623	426
Δ	ω_p	rad/sec	0.080	0.085
	ζ_p		0.162	0.141
	ω_{sp}	rad/sec	0.915	0.740
	ζ_{sp}		0.631	0.745
$N^{\theta}_{\delta_e}$	A_θ	sec^{-2}	−1.99	−1.36
	$1/T_{\theta_1}$	sec^{-1}	0.019	0.028
	$1/T_{\theta_2}$	sec^{-1}	0.580	0.555
$N^{\dot{h}}_{\delta_e}$	A_h	$ft/sec^2/rad$	59.41	47.20
	$1/T_{h_1}$	sec^{-1}	0.020	0.019
	$1/T_{h_2}$	sec^{-1}	−3.24	−2.39
	$1/T_{h_3}$	sec^{-1}	3.66	2.81

TABLE 1-c

SELECTED LATERAL TRANSFER FUNCTIONS FOR MDAC-2 LCR

	FLIGHT CONDITION		1	2	3
	h V	ft ft/sec	20,000 623	10,000 426	625 454
Δ	$1/T_s$ $1/T_R$ ω_d ζ_d	sec^{-1} sec^{-1} rad/sec 	-0.005 1.14 0.770 0.330	-0.012 1.02 0.690 0.394	-0.015 1.26 0.862 0.528
$N^{\varphi}_{\delta_a}$	A_φ ω_φ ζ_φ	sec^{-2} rad/sec 	3.83 0.737 0.336	2.15 0.622 0.399	1.62 0.689 0.468
$N^{r}_{\delta_a}$	A_r $1/T_{r_1}$ $\omega_r(1/T_{r_2})$ $\zeta_r(1/T_{r_3})$	sec^{-2} sec^{-1} rad/sec 	0.012 3.61 1.49 0.672	0.0083 0.796 2.85 0.262	-0.076 -0.654 (0.445) (1.99)
$N^{\beta}_{\delta_a}$	A_β $1/T_{\beta_1}$ $1/T_{\beta_2}(\omega_\beta)$ $1/T_{\beta_3}(\zeta_\beta)$	sec^{-1} sec^{-1} sec^{-1} sec^{-1}	-0.0066 -28.4 (0.478) (0.97)	-0.0062 -34.56 0.268 0.637	-0.0022 -145.3 0.124 0.754
$N^{\varphi}_{\delta_r}$	A_φ $1/T_{\varphi_1}(\omega_\varphi)$ $1/T_{\varphi_2}(\zeta_\varphi)$	sec^{-2} sec^{-1} sec^{-1}	1.78 0.407 -0.255	1.11 0.413 -0.346	1.66 0.554 -0.545
$N^{\beta}_{\delta_r}$	A_β $1/T_{\beta_1}$ $1/T_{\beta_2}$ $1/T_{\beta_3}$	sec^{-1} sec^{-1} sec^{-1} sec^{-1}	0.041 -0.0093 1.10 19.75	0.039 -0.025 0.969 14.46	0.055 -0.037 1.09 17.14

TABLE 2

LONGITUDINAL HANDLING QUALITY FACTORS, MDAC-2 LCR

	DESIRABLE VALUES	FLIGHT CONDITION 1	FLIGHT CONDITION 2
ω_{sp}	(see Fig. 8)	0.915	0.74
ζ_{sp}		0.631	0.75
$1/T_{\theta_2}$	> 0.4	0.58	0.55
σ_a	> 0.5	0.29	0.17

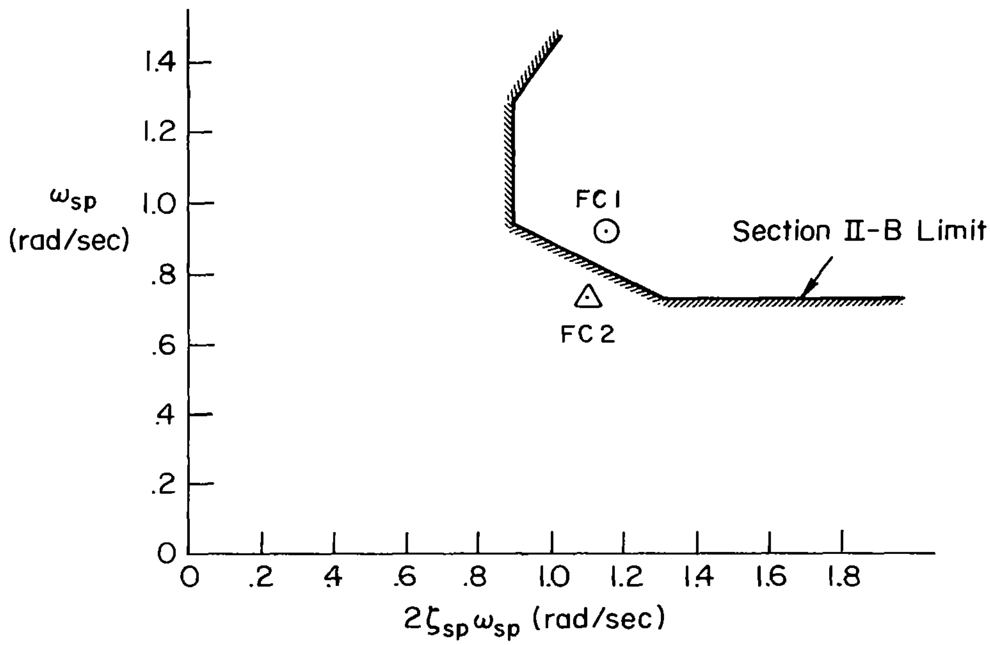


Figure 8. Short-Period Frequency, MDAC-2 LCR

Key lateral handling qualities parameters are listed in Table 3.

TABLE 3

LATERAL HANDLING QUALITY FACTORS, MDAC-2 LCR

	DESIRABLE VALUES	FLIGHT CONDITION 1	FLIGHT CONDITION 2	FLIGHT CONDITION 3
ω_d	> 0.4 rad sec	0.77	0.69	0.86
$\zeta_d\omega_d$	> 0.15 rad/sec	0.25	0.27	0.45
$1/T_R$	> 1.0 sec^{-1}	1.23	1.02	1.26
$1/T_s$	> −0.035 sec^{-1}	−0.005	−0.012	−0.015
ω_φ/ω_d*	0.75 - 1.1	0.96	0.90	0.79
p_{max}	> 10 deg/sec	30.8	34.2	15.8

*This criterion is a measure of roll control problems and is roughly equivalent to the p_{osc}/p_{av} criterion of 8785B.

The characteristics listed there are all quite good. Likewise the heading control criterion also indicates a satisfactory rating, see Fig. 9. Overall the lateral characteristics should be quite satisfactory.

B. SIMULATOR EVALUATION OF MDAC-2 LCR

Prior to the simulator evaluation of this configuration NASA made the decision to stop work on the low-cross-range orbiter. Consequently, very little time was spent evaluating this configuration. In their brief exposure to it, the pilots considered this configuration to be generally satisfactory. As the analysis indicated no serious longitudinal problems and good lateral characteristics, the analytical/experimental correlation is reasonably good.

C. ANALYTICAL HANDLING QUALITIES SURVEY FOR NAR HCR-134C

The longitudinal and lateral handling characteristics of the NAR HCR-134C, Fig. 10, were analyzed at three flight conditions selected from the trajectories in Ref. 5. These flight conditions are summarized in Fig. 11.

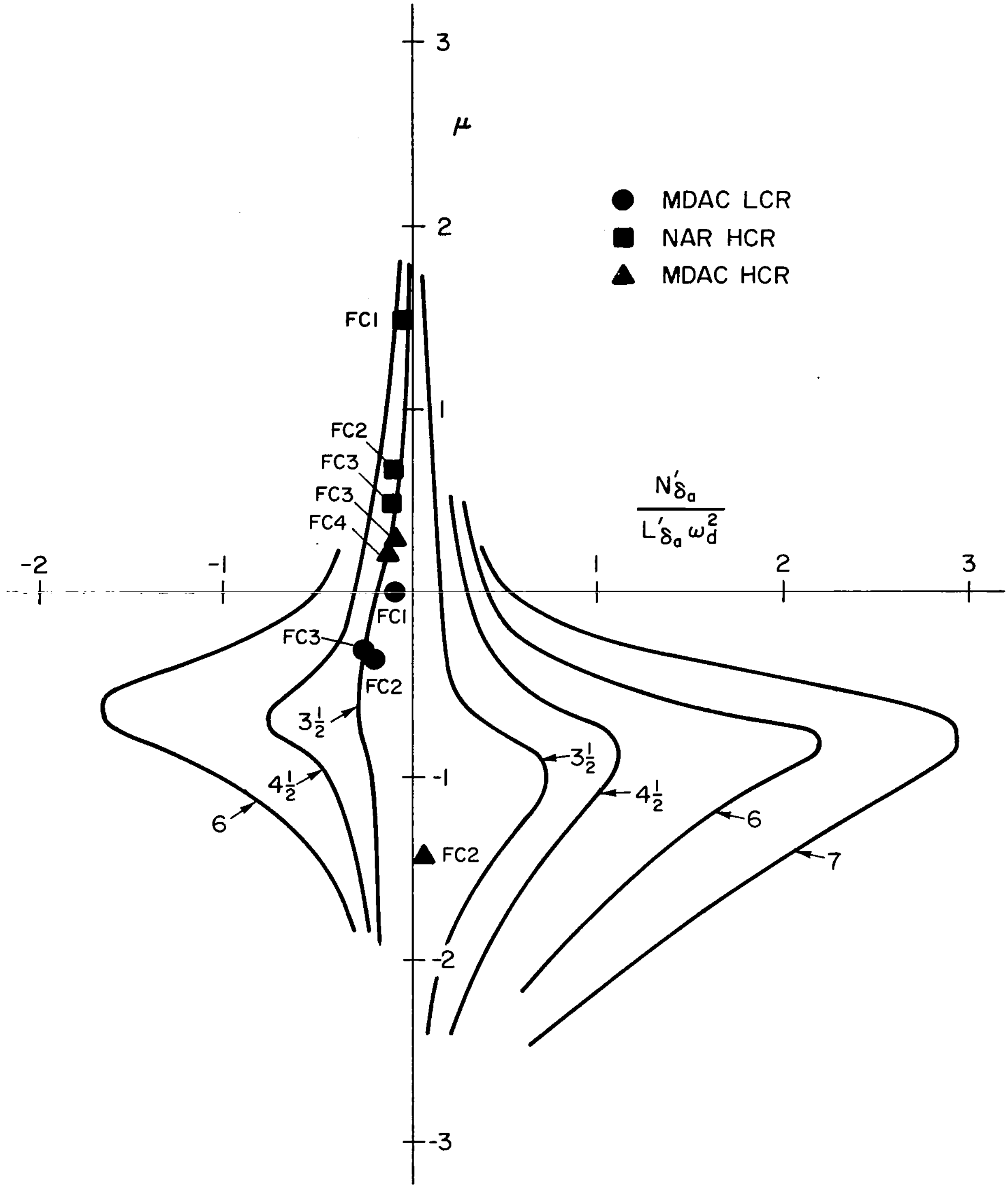


Figure 9. Heading Control Boundaries For $|N'_{\delta_a}/L'_{\delta_a}| > 0.04$

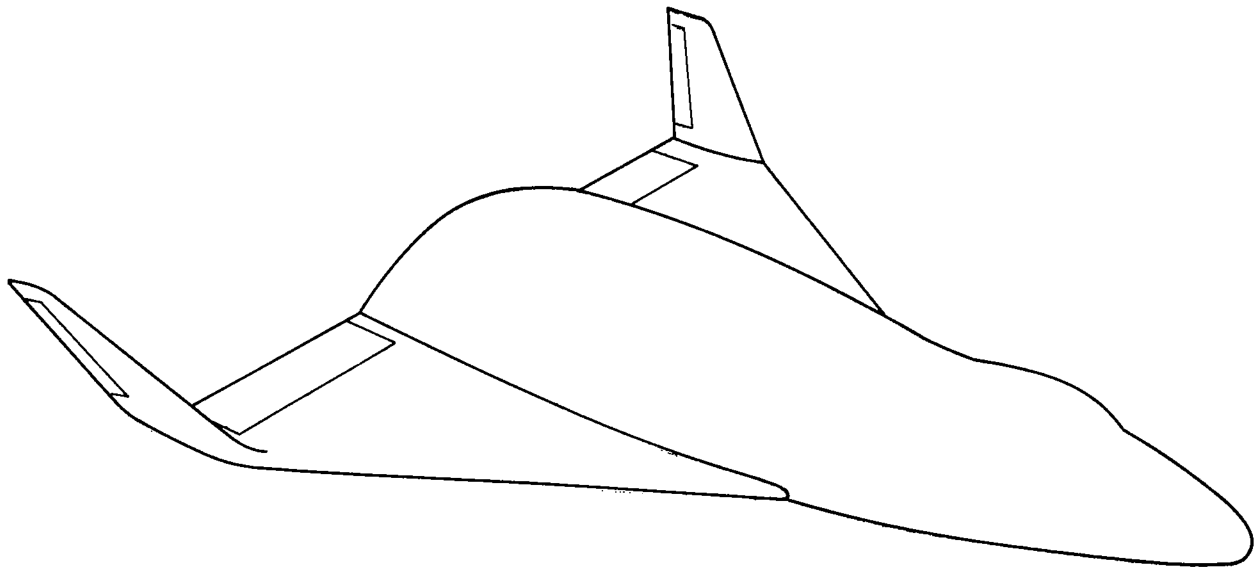
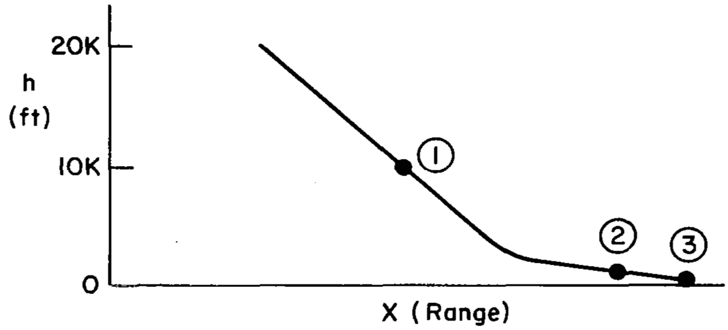


Figure 10. NAR HCR 134-C Configuration



FLIGHT CONDITION	h ft	V kt	M	Q PSF	C_L	α deg	REMARKS
1	10,000	367	0.57	330	0.106	5.0	nominal glide $\gamma = -10$ deg
2	300	233	0.35	185	0.189	8.5	float, $\gamma = -2.5$ deg
3	0	188	0.28	120	0.29	12.0	max L/D near touchdown $\gamma = 0$

Figure 11. Summary of Selected Flight Conditions for NAR HCR-134C

The stability derivatives and key transfer functions are summarized in Table 4 for these three flight conditions plus one at high altitude. The low altitude characteristics will be discussed first.

A summary of pertinent longitudinal handling quality factors is given in Table 5 and Fig. 12. The short period damping is seen to be close to the minimum damping boundary in Fig. 12. The values of the PIO parameter, σ_a, are somewhat less than the desired value so there may be some PIO tendencies. There are no serious problems so the longitudinal characteristics should be marginally satisfactory, pilot rating approximately 3.5.

TABLE 4-a

DIMENSIONAL STABILITY DERIVATIVES
FOR NAR HCR 134C

STABILITY AXIS DERIVATIVES

		FLIGHT CONDITION 1	FLIGHT CONDITION 2	FLIGHT CONDITION 3	FLIGHT CONDITION 4
h	ft	10,000	300	0	100,000
V	ft/sec	620	394	318	2,973
α	deg	5.0	8.5	12.0	15
W	lb	212,740	212,740	212,740	212,740
X_u	sec^{-1}	−0.02	−0.018	−0.023	−0.0078
X_w	sec^{-1}	−0.018	0.0026	−0.042	−0.010
Z_u	sec^{-1}	−0.106	−0.164	−0.204	−0.0165
Z_w	sec^{-1}	−1.15	−0.986	−0.808	−0.063
$Z_{\dot{w}}$	—	−0.086	−0.115	−0.131	−0.0015
M_u	rad/ft-sec	0	0	0	0
M_α	sec^{-2}	−4.10	−1.85	−1.05	−0.570
$M_{\dot{\alpha}}$	sec^{-1}	0.249	0.214	0.162	0.015
M_q	sec^{-1}	−0.753	−0.646	−0.526	−0.052
X_{δ_e}	$ft/sec^2/rad$	−21.2	−12.6	−10.2	8.58
Z_{δ_e}	$ft/sec^2/rad$	−297.5	−154.6	−95.1	−3.88
M_{δ_e}	sec^{-2}	−3.97	−2.05	−1.28	−0.159
Y_β	$ft/sec^2/rad$	−131.9	−72.2	−47.6	−97.4
L'_β	sec^{-2}	−5.11	−4.03	−4.35	−1.74
N'_β	sec^{-2}	0.980	0.694	0.627	0.106
L'_p	sec^{-1}	−0.990	−0.820	−0.700	−0.060
N'_p	sec^{-1}	−0.073	−0.077	−0.105	−0.0084
L'_r	sec^{-1}	2.66	2.32	1.87	0.145
N'_r	sec^{-1}	−0.225	−0.297	−0.320	−0.041
Y_{δ_a}	$ft/sec^2/rad$	0	0	0	0
L'_{δ_a}	sec^{-2}	10.2	5.15	3.07	0.679
N'_{δ_a}	sec^{-2}	−0.499	−0.557	−0.490	−0.170
Y_{δ_r}	$ft/sec^2/rad$	89.6	48.1	28.9	16.3
L'_{δ_r}	sec^{-2}	7.20	3.28	2.05	0.700
N'_{δ_r}	sec^{-2}	−2.04	−1.19	−0.846	−0.525

TABLE 4-b

SELECTED LONGITUDINAL TRANSFER FUNCTIONS FOR NAR HCR 134C

	FLIGHT CONDITION		1	2	3	4
	h	ft	10,000	300	0	100,000
	V	ft/sec	620	394	318	2,973
Δ	ω_p	rad/sec	0.068	0.100	0.123	0.016
	ζ_p	—	0.186	0.067	0.023	0.335
	ω_{sp}	rad/sec	2.14	1.49	1.14	0.756
	ζ_{sp}	—	0.369	0.450	0.488	0.064
$N^{\theta}_{\delta_e}$	A_θ	sec^{-2}	−4.43	−2.36	−1.50	−0.159
	$1/T_{\theta_1}$	sec^{-2}	0.023	0.027	0.018	0.00091
	$1/T_{\theta_2}$	sec^{-1}	0.580	0.538	0.485	0.064
$N^{\dot{h}}_{\delta_e}$	A_h	$ft/sec^2/rad$	297.0	155.0	95.1	3.11
	$1/T_{h_1}$	sec^{-1}	0.023	0.0083	−0.019	−0.0012
	$1/T_{h_2}$	sec^{-1}	−2.39	−1.90	−1.64	−3.08
	$1/T_{h_3}$	sec^{-1}	2.20	1.73	1.47	2.93

TABLE 4-c

SELECTED LATERAL TRANSFER FUNCTIONS FOR NAR HCR 134C

	FLIGHT CONDITION		1	2	3	4
	h	ft	10,000	300	0	100,000
	V	ft/sec	620	394	318	2,973
Δ	$1/T_s$	sec^{-1}	−0.036	−0.023	0.016	0.016
	$1/T_R$	sec^{-1}	1.24	1.15	1.16	0.258
	ω_d	rad/sec	1.20	1.07	1.09	0.384
	ζ_d	—	0.095	0.082	−0.0029	−0.184
$N^{\varphi}_{\delta_a}$	A_φ	sec^{-2}	1.03	5.18	3.06	0.694
	$\omega_\varphi(1/T_{\varphi_1})$	rad/sec	0.865	0.516	(0.354)	(0.586)
	$\zeta_\varphi(1/T_{\varphi_2})$	—	0.190	0.229	(−0.183)	(−0.547)
$N^{r}_{\delta_a}$	A_r	sec^{-2}	−0.499	−0.557	−0.490	−0.170
	$1/T_{r_1}$	sec^{-1}	−0.418	−0.251	1.38	0.287
	$\omega_r(1/T_{r_2})$	rad/sec	(0.787)	(0.546)	0.177	0.222
	$\zeta_r(1/T_{r_3})$	—	(2.32)	(1.42)	0.351	−0.362
$N^{\beta}_{\delta_a}$	A_β	sec^{-2}	0.499	0.557	0.490	0.170
	$1/T_{\beta_1}$	sec^{-1}	0.035	0.018	0.0068	0.0021
	$1/T_{\beta_2}$	sec^{-1}	3.50	2.27	1.98	0.136
$N^{\varphi}_{\delta_r}$	A_φ	sec^{-2}	7.56	3.33	2.05	0.745
	$1/T_{\varphi_1}(\omega_\varphi)$	sec^{-1}	−0.903	−1.19	−1.39	−1.08
	$1/T_{\varphi_2}(\zeta_\varphi)$	sec^{-1}	0.571	0.704	0.896	1.04
$N^{\beta}_{\delta_r}$	A_β	sec^{-1}	0.145	0.122	0.091	0.0055
	$1/T_{\beta_1}$	sec^{-1}	−0.055	−0.085	−0.083	−0.0095
	$1/T_{\beta_2}$	sec^{-1}	1.56	1.43	1.38	0.096
	$1/T_{\beta_3}$	sec^{-1}	13.73	9.51	9.04	9.55

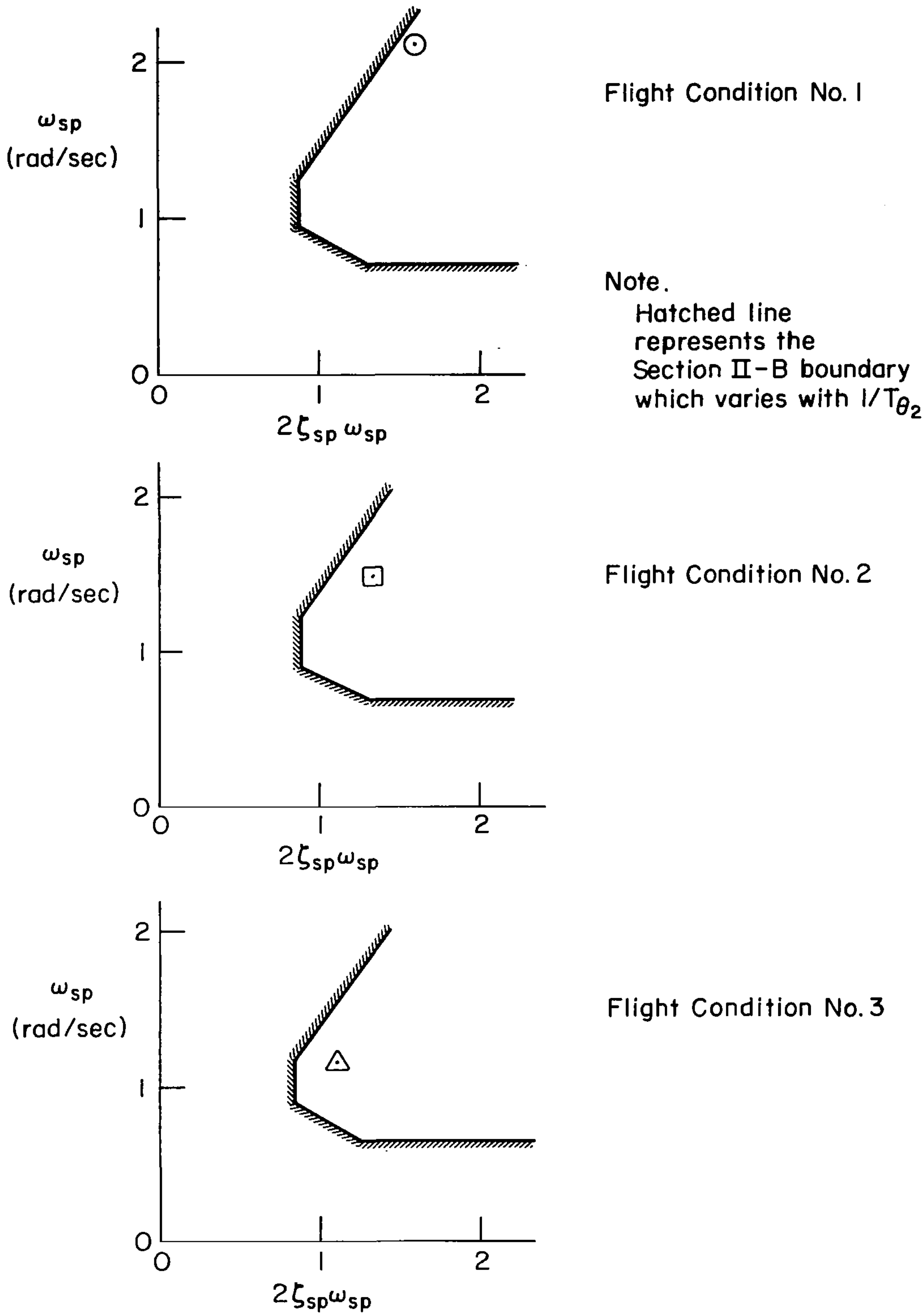


Figure 12. NAR HCR 134-C Short-Period Characteristics

TABLE 5

LONGITUDINAL HANDLING QUALITIES FACTORS FOR NAR HCR-134C

	DESIRABLE VALUES	FLIGHT CONDITION 1	FLIGHT CONDITION 2	FLIGHT CONDITION 3
ω_{sp}	(see Fig. 12)	2.14	1.49	1.14
ζ_{sp}		0.369	0.450	0.488
$1/T_{\theta 2}$	> 0.4	0.58	0.54	0.49
σ_a	> 0.5	0.50	0.40	0.31

A summary of pertinent lateral handling quality factors for the low altitude flight conditions is given in Table 6, and the heading control

TABLE 6

LATERAL HANDLING QUALITIES FACTORS FOR NAR HCR-134C

	DESIRABLE VALUES	FLIGHT CONDITION 1	FLIGHT CONDITION 2	FLIGHT CONDITION 3
ω_d	> 0.4 rad/sec	1.20	1.07	1.09
$\zeta_d\omega_d$	> 0.15 rad/sec	0.11	0.09	−0.003
$1/T_R$	> 1 sec^{-1}	1.24	1.15	1.16
$1/T_s$	> −0.035 sec^{-1}	−0.036	−0.023	0.016
ω_φ/ω_d	0.75 - 1.1	0.723	0.483	real roots
p_{max}	> 10 deg/sec	43	10.4	roll reversal

criterion is shown in Fig. 9. While heading control would be no problem according to Fig. 9, provided other qualities were in the satisfactory region, there are obvious overriding deficiencies from Table 6 which may be summarized as follows.

- Low Dutch roll damping — all flight conditions.
- Roll rate reversals due to $\omega_\varphi/\omega_d < 0.75$ — all cases.
- Roll angle reversal at max L/D (F.C. 3).

The most serious is the roll reversal near touchdown (F.C. 3). This means the aircraft is unflyable aileron-alone. It may be flyable if the pilot uses the rudder to improve the turn coordination but it is certainly not an acceptable configuration (rating > 6.5).

The high altitude characteristics of this vehicle (Flight Condition 4) are poor. This can easily be seen by looking at the pitch and roll dynamics. The pitch/elevator frequency response is shown in Fig. 13.

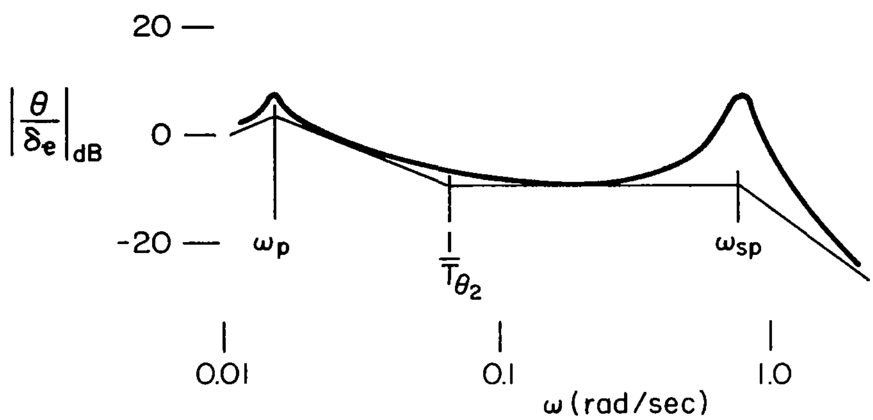


Figure 13. Attitude Control Characteristics of NAR HCR 134C; h = 100,000 ft, M = 3

The following observations can be made from Fig. 13:

- The major deficiency is the very low short period damping (ζ_{sp} = 0.064) which will make precise attitude control difficult (i.e., requires pilot lead).
- Low $1/T_{\theta_2}$ (0.064 sec^{-1}) will result in very slow flight path changes with attitude. This is not necessarily a problem at high altitude where tight flight path control is not required. However it will lead to pitch overshoot problems for tight attitude control.

The pitch control should appear slightly sluggish with a tendency for very large overshoots. Considerable pilot lead or lag/lead equalization will be required to accurately control pitch attitude. The characteristics are definitely not satisfactory for normal operations but may be acceptable for an emergency situation.

The roll/aileron characteristics are summarized in terms of pole/zero locations in Fig. 14.

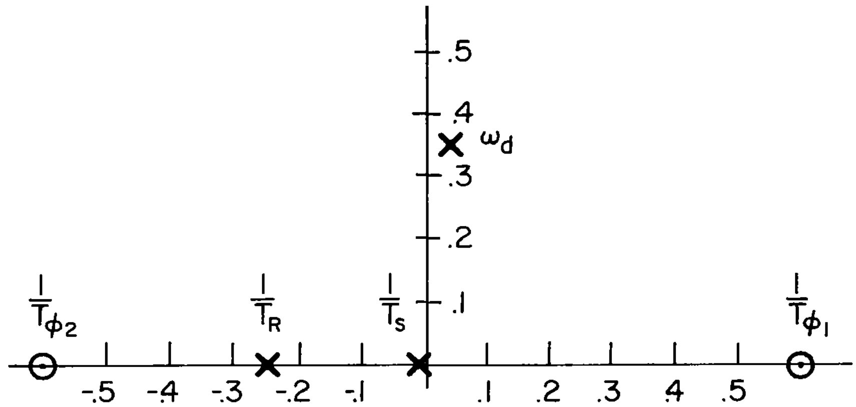


Figure 14. Pole-Zero Locations of φ/δ_a Transfer Function
h = 100,000 ft, M = 3, NAR HCR 134-C

Any attempt by the pilot at closing the roll loop will drive the spiral mode unstable (i.e., into $1/T_{\varphi_1}$); clearly an unacceptable situation. Other problems with this vehicle are negative dutch roll damping and very low roll damping. Based on these factors, the vehicle is probably unflyable.

D. SIMULATOR EVALUATION OF NAR HCR 134-C

A summary of pilot comments for longitudinal control at low altitude is given below.

- "Vehicle is a little bit on the lightly damped side."
- "If you're not careful you can get a little bit of a PIO maneuver in pitch going....tends to bobble attitude."
- "There's a tendency to chase the glideslope a little bit."

The pilot commentary is consistent with the analysis which indicated that short period damping is marginal. Comments concerning minor PIO or bobbling of attitude are consistent with the values of the PIO parameter, σ_a. However, it is believed that the side-arm controller and series trim device used on these tests are at least partially responsible for the PIO tendencies, see Appendix C. Pilot ratings longitudinally were given as 4-5 without turbulence with a one rating point degradation with turbulence on.

As expected from the analysis, the lateral control was rated as quite poor for the initial approach phase (-10° glide) and completely unacceptable for final flare and touchdown. A summary of the pertinent pilot commentary is given below.

- "The initial approach phase at -10° is flyable. In fact, I can deliberately make offsets and bring it back on IFR. The roll control is a bit difficult but not impossible."

- "The roll control seems to get progressively harder, and then right at the touchdown, the thing becomes unflyable as far as I'm concerned. Once I flare the vehicle I've had it. I get completely lost as far as roll control goes."

The roll control was rated as 5 to 6 on the -10° glide, going to a 10 at final flare and touchdown. Introduction of turbulence degraded the initial rating to a 7 or 8.

The pilots were unable to control the vehicle in roll at the high altitude flight condition. Evaluation of pitch control was difficult since the vehicle became inverted shortly after initiating each run. However, the pilots did feel that the pitch control was probably adequate for an emergency situation.

E. ANALYTICAL HANDLING QUALITIES SURVEY FOR MDAC HCR

The handling qualities of the MDAC HCR vehicle (Model 050B), Fig. 15, were analyzed at the four flight conditions summarized in Table 7. Stability

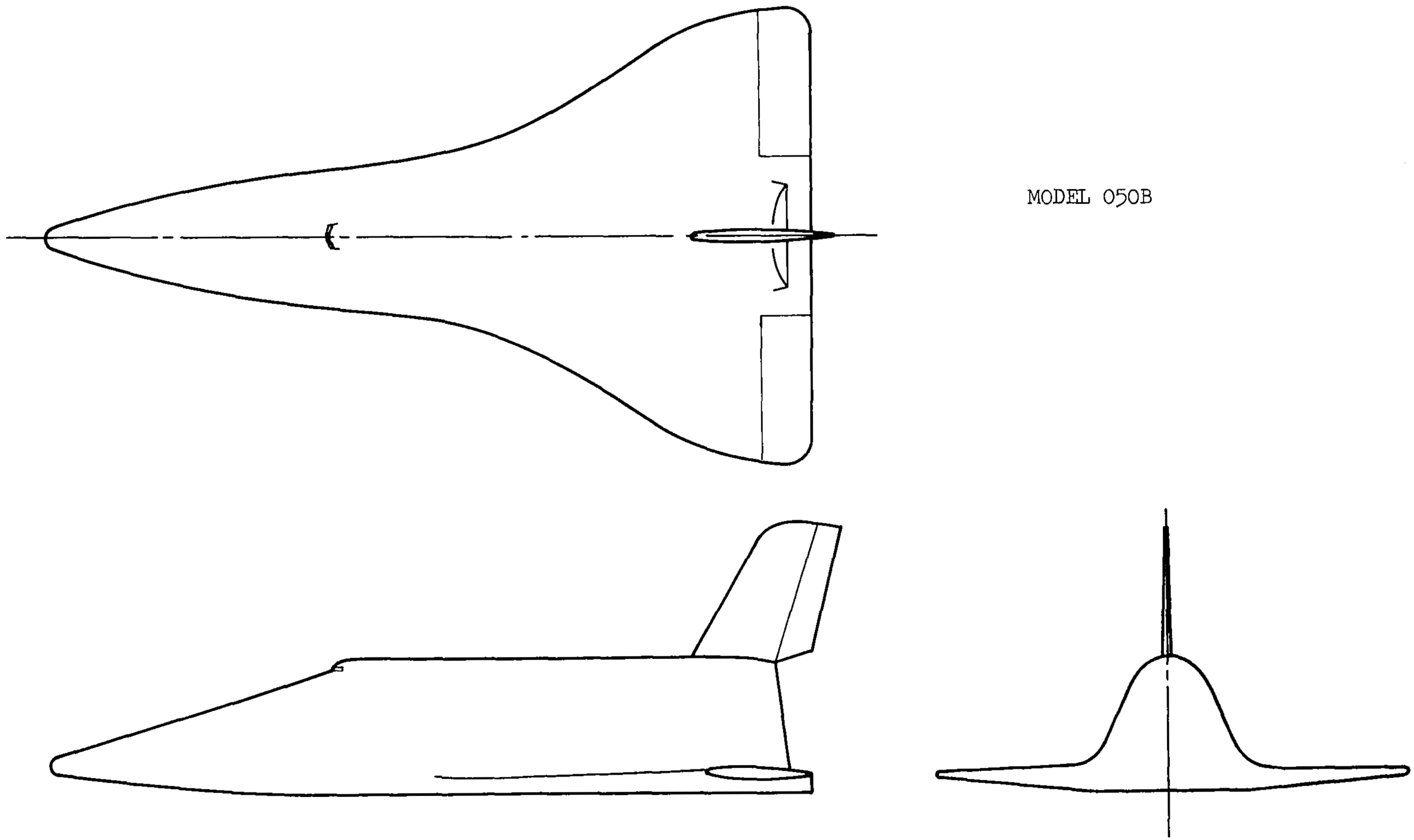


Figure 15. MDAC HCR Configuration

TABLE 7

SUMMARY OF FLIGHT CONDITIONS

FLIGHT CONDITION	h	V		M	C_L	α	Q	γ	$\delta_{e_{TRIM}}$
	FT	KTS	FPS	—	—	DEG	PSF	DEG	DEG
1	90000	1160	1965	2.0	0.485	14	100	−21	−30.
2	10000	383	648	0.6	0.13	2	370	−14.9	−4.8
3	S.L.	224	378	0.34	0.28	7	170	0	−5.0
4	S.L.	180	304	0.27	0.432	12	110	0	−7.0

derivatives and key transfer functions are listed in Table 8. Flight Condition 1 is a high altitude and Mach condition. Flight Condition 2 is a typical trimmed glide case. Flight Conditions 3 and 4 are representative of low altitude, low speed flight during the terminal glide and touchdown phase.

The longitudinal characteristics for Flight Condition 1 are unusual. The pitch/elevator transfer function is

$$\theta/\delta_e \doteq \frac{-0.52(s + 0.097)}{(s + 0.32)[s^2 + 2(-0.37)(0.24)s + (0.24)^2]}$$

Because of the lack of static stability, the classical phugoid and short period modes are not present. Due to the high altitude, the poles and zeros are all relatively small.

While the vehicle is unstable for this flight condition, it is flyable. In fact, a pure gain $\theta \rightarrow \delta_e$ feedback will stabilize it. To the pilot the pitch control will appear similar to K/s^2, and he will have to exercise continuous control. The longitudinal characteristics are therefore unsatisfactory and probably unacceptable (PR > 6.5).

A summary of the longitudinal handling quality factors for Flight Conditions 2-4 is given in Table 9.

TABLE 8-a

DIMENSIONAL STABILITY DERIVATIVES
FOR MDAC HCR

FUSELAGE REFERENCE AXIS DERIVATIVES

		FLIGHT CONDITION 1	FLIGHT CONDITION 2	FLIGHT CONDITION 3	FLIGHT CONDITION 4
h	ft	90,000	10,000	S.L.	S.L.
V	ft/sec	1,965	648	378	304
α	deg	14	2	7	12
W	lb	253,448	253,448	253,448	253,448
X_u	sec^{-1}	−0.00058	−0.0307	−0.039	−0.042
X_w	sec^{-1}	−0.0107	0.219	0.154	0.104
Z_u	sec^{-1}	−0.0081	−0.057	−0.103	−0.094
Z_w	sec^{-1}	−0.094	−1.01	−0.664	−0.630
$Z_{\dot{w}}$	—	0	0	0	0
M_u	rad/ft−sec	0.0002	0	0.00019	0.00051
M_α	sec^{-2}	0.0014	−3.86	−0.852	−0.813
$M_{\dot{\alpha}}$	sec^{-1}	−0.0077	−0.070	−0.055	−0.043
M_q	sec^{-1}	−0.070	−0.315	−0.243	−0.193
X_{δ_e}	$ft/sec^2/rad$	−10.1	7.59	−3.92	−7.52
Z_{δ_e}	$ft/sec^2/rad$	−13.4	−189.6	−113.1	−67.6
M_{δ_e}	sec^{-2}	−0.52	−4.61	−2.58	−1.63
Y_β	$ft/sec^2/rad$	−53.5	−219.6	−102.5	−58.5
L'_β	sec^{-2}	−2.12	−8.93	−7.16	−5.66
N'_β	sec^{-2}	−0.178	0.465	0.257	0.143
L'_p	sec^{-1}	−0.079	−0.925	−0.632	−0.427
N'_p	sec^{-1}	−0.00019	−0.022	−0.028	−0.035
L'_r	sec^{-1}	0.049	0.406	0.380	0.314
N'_r	sec^{-1}	−0.015	−0.209	−0.157	−0.124
Y_{δ_a}	$ft/sec^2/rad$	1.61	−38.5	−15.9	−11.3
L'_{δ_a}	sec^{-2}	1.17	9.05	5.77	3.64
N'_{δ_a}	sec^{-2}	−0.061	0.726	0.209	0.073
Y_{δ_r}	$ft/sec^2/rad$	2.00	28.5	13.3	8.40
L'_{δ_r}	sec^{-2}	0.312	2.50	1.17	0.735
N'_{δ_r}	sec^{-2}	−0.083	−0.830	−0.388	−0.244

TABLE 8-b

SELECTED LONGITUDINAL TRANSFER FUNCTIONS FOR MDAC HCR

	FLIGHT CONDITION		1	2	3	4
	h	ft	90,000	10,000	S.L.	S.L.
	V	ft/sec	1,965	648	378	304
Δ	$\omega_p(1/T_{p_1})$	rad/sec	(0.032)	0.056	0.105	0.138
	$\zeta_p(1/T_{p_2})$	—	(0.322)	0.380	0.164	0.166
	ω_{sp}	rad/sec	0.243	2.04	1.01	0.960
	ζ_{sp}	—	−0.372	0.339	0.478	0.449
$N^{\theta}_{\delta_e}$	A_θ	sec^{-2}	−0.520	−4.59	−2.57	−1.62
	$1/T_{\theta_1}$	sec^{-1}	0.0028	0.049	0.074	0.0 75
	$1/T_{\theta_2}$	sec^{-1}	0.097	0.752	0.535	0.493
$N^{\dot{h}}_{\delta_e}$	A_h	$ft/sec^2/rad$	14.56	186.5	111.8	64.55
	$1/T_{h_1}$	sec^{-1}	0.0025	0.058	0.043	0.028
	$1/T_{h_2}$	sec^{-1}	−2.48	−3.13	−2.10	−1.85
	$1/T_{h_3}$	sec^{-1}	2.56	3.54	2.36	2.05

TABLE 8-c

SELECTED LATERAL TRANSFER FUNCTIONS
FOR MDAC HCR

	FLIGHT CONDITION		1	2	3	4
	h	ft	90,000	10,000	S.L.	S.L.
	V	ft/sec	1,965	648	378	304
Δ	$1/T_s$	sec^{-1}	0.032	0.081	0.082	0.071
	$1/T_R$	sec^{-1}	0.058	1.14	0.813	0.631
	ω_d	rad/sec	0.583	0.980	1.11	1.19
	ζ_d	—	0.026	0.131	0.074	0.018
$N^{\varphi}_{\delta_a}$	A_{φ}	sec^{-2}	1.17	8.89	5.79	3.65
	$\omega_{\varphi}(1/T_{\varphi_1})$	rad/sec	(0.538)	1.13	0.755	0.540
	$\zeta_{\varphi}(1/T_{\varphi_2}$	—	(−0.500)	0.280	0.325	0.349
$N^{r}_{\delta_a}$	A_r	sec^{-1}	−0.061	0.726	0.209	0.073
	$1/T_{r_1}$	sec^{-1}	0.067	0.991	0.613	0.445
	$\omega_r(1/T_{r_2})$	rad/sec	1.16	0.849	1.40	1.73
	$\zeta_r(1/T_{r_3})$	—	0.194	−0.022	−0.195	−0.478
$N^{\beta}_{\delta_a}$	A_{β}	sec^{-1}	0.00082	−0.060	−0.042	−0.038
	$1/T_{\beta_1}$	sec^{-1}	0.010	0.449	0.145	0.093
	$1/T_{\beta_2}$	sec^{-1}	0.070	−0.470	1.10	0.735
	$1/T_{\beta_3}$	sec^{-1}	416.8	8.04	−12.3	−18.51
$N^{\varphi}_{\delta_r}$	A_{φ}	sec^{-2}	0.322	2.69	1.12	0.683
	$1/T_{\varphi_1}(\omega_{\varphi})$	sec^{-1}	0.835	1.69	1.53	1.37
	$1/T_{\varphi_2}(\zeta_{\varphi})$	sec^{-1}	−0.810	−1.36	−1.48	−1.42
$N^{\beta}_{\delta_r}$	A_{β}	sec^{-1}	0.0010	0.044	0.035	0.028
	$1/T_{\beta_1}$	sec^{-1}	0.0019	0.019	0.0030	−0.0065
	$1/T_{\beta_2}$	sec^{-1}	0.074	1.03	0.714	0.525
	$1/T_{\beta_3}$	sec^{-1}	153.2	208.4	15.08	14.1

TABLE 9

LONGITUDINAL HANDLING QUALITIES FACTORS MDAC HCR

	DESIRABLE VALUES	FLIGHT CONDITION 2	FLIGHT CONDITION 3	FLIGHT CONDITION 4
ω_{sp}	(see Fig. 16)	2.04	1.01	0.96
ζ_{sp}		0.34	0.48	0.45
$1/T_{\theta_2}$	> 0.4	0.75	0.53	0.49
σ_a	> 0.5	0.31	0.22	0.24

The short period characteristics are compared with the proposed criteria of Section II-B in Fig. 16. The points are near the minimum frequency and damping boundaries indicating that the pitch attitude dynamics are marginal. The PIO parameter, σ_a, is also somewhat less than the desired value. There are no serious problems so the longitudinal characteristics for low altitudes should be marginally satisfactory, i.e., pilot rating of approximately 3.5.

A summary of pertinent lateral handling quality factors for each of the four flight conditions is given in Table 10. Flight Condition 1 is unflyable without the rudder because of the roll reversal. With good rudder characteristics it might be flyable but should still be unacceptable (PR > 6.5).

The aileron rudder coordination characteristics for Flight Conditions 2-4 are plotted on the proposed boundaries in Fig. 9. Based on these boundaries, Flight Condition 2 should have quite satisfactory, and Flight Conditions 3 and 4 should have marginal, but satisfactory, heading control.

However, other potential problem areas that can be identified from Table 10 are:

- Dutch roll damping is too low, especially for Flight Conditions 3 and 4.
- Roll damping is too low for satisfactory ratings, especially Flight Condition 4.
- Roll rate reversal or "racheting" will occur for Flight Conditions 3 and 4 (ω_φ/ω_d too low).

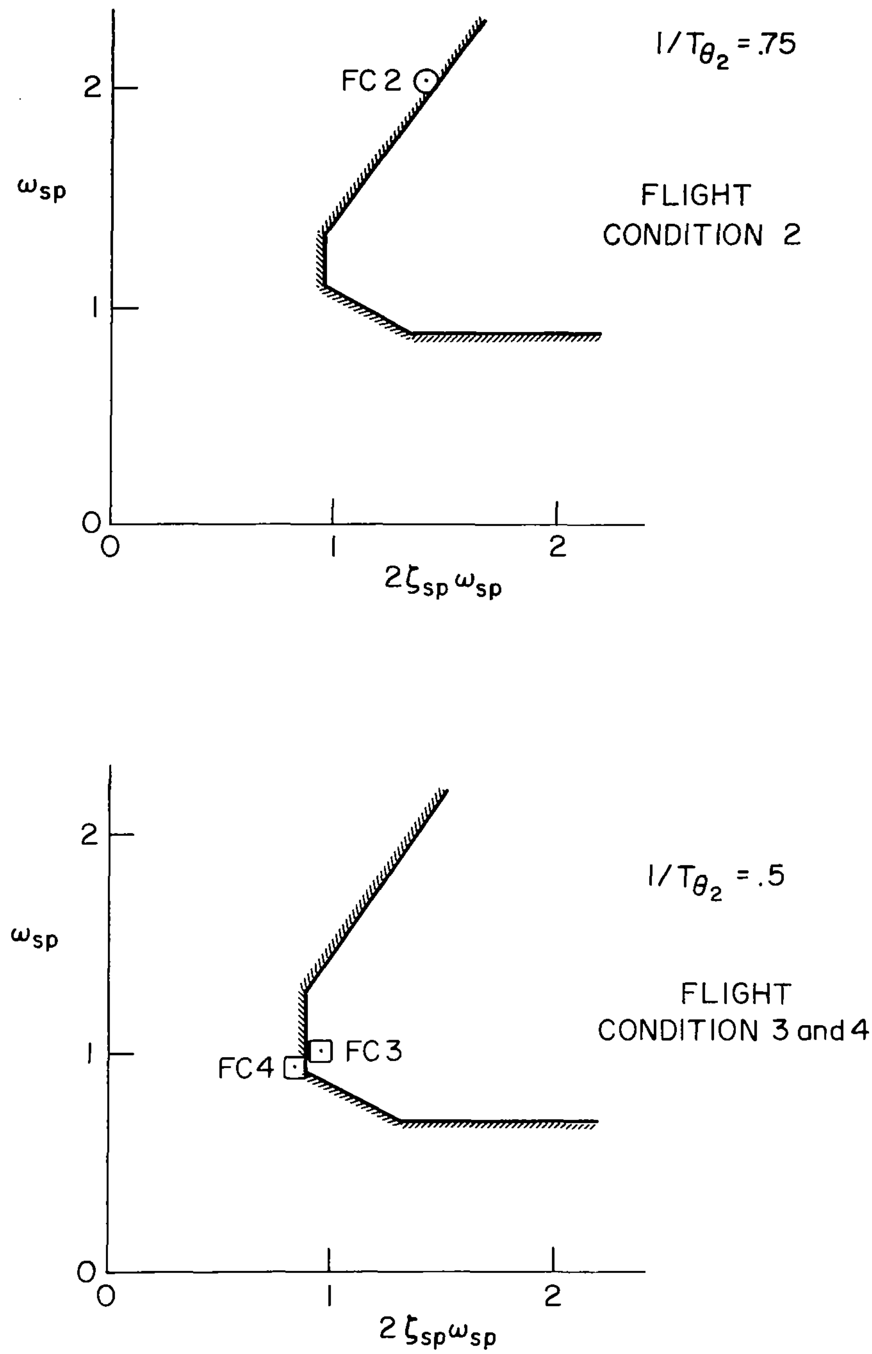


Figure 16. MDAC HCR Short Period Characteristics

TABLE 10

LATERAL HANDLING QUALITY FACTORS FOR MDAC HCR

	DESIRABLE VALUES	FLIGHT CONDITION 1	FLIGHT CONDITION 2	FLIGHT CONDITION 3	FLIGHT CONDITION 4
M		2.0	0.6	0.34	0.27
α		14°	2°	7°	12°
ω_d	> 0.4 rad/sec	0.583	0.980	1.11	1.19
$\zeta_d \omega_d$	> 0.15 rad/sec	0.015	0.13	0.082	0.021
$1/T_S$	> -0.035 sec^{-1}	0.032	0.081	0.082	0.071
$1/T_R$	> 1.0 sec^{-1}	0.058	1.14	0.812	0.631
ω_φ/ω_d	0.75 – 1.1	Roll reversal Real roots at ±0.5	1.16	0.68	0.45
p_{max}*	> 10°/sec	-161°/sec	107°/sec	32.8°/sec	12°/sec

$^*\delta_{a_{max}} = 10^{\circ}$

Flight Condition 2 shows no significant deficiencies. The approach and landing flight conditions (3 and 4) will probably be moderately objectionable but acceptable since there are no serious problems ($3.5 < PR < 6.5$).

F. SIMULATOR EVALUATION OF MDAC HCR

Handling quality evaluations were performed by two NASA pilots in two altitude regimes; 80,000 feet and 10,000 ft to sea level. The initial conditions used are summarized in Table 11 below.

TABLE 11

INITIAL CONDITIONS

High Altitude		Low Altitude	
		Speedbrake Off	Speed Brake Rigged Half Up
h	80,000 ft	11,630 ft	11,630 ft
M	2.0	0.6	0.5
γ	-8°	-11.6°	-11.6°
α	10°	2.2°	4.0°
δ_e	-30°	-4.3°	-5°

A summary of the comments and pilot ratings is given in Table 12.

As expected from the analysis, the high altitude flight condition (F.C. 1) was unacceptable for both lateral and longitudinal control. The main problem laterally was the roll reversal characteristics which resulted in an unstable pilot-airframe system. It was extremely difficult to keep the vehicle from rolling over on its back when using rudders and impossible if rudders were not used. Longitudinally, the main problem was the negative static margin for angles of attack greater than 10°. Both pilots found that by keeping α less than 10°, longitudinal control could be maintained.

Pilot B rated the low altitude flight condition a 2 both laterally and longitudinally except for the period just before touchdown. At this point

TABLE 12. PILOT COMMENTARY FOR MDAC HCR

	High Altitude	PR	Low Altitude	PR
Roll Control	• Roll reversal is uncontrollable • Rudders help but not much	Pilot A 10 Pilot B 7 1/2	• OK until near touch-down where roll power is too low. PR near touchdown is 7-8 due to low roll power (Pilot B)	Pilot A 2
Turn Coordination and Heading Control	• Impossible		• No rudder required initially PR = 2 • Turn coordination required near touch-down PR = 4	Pilot A 3
Localizer and Runway Tracking	• Localizer tracking impossible		• Initial PR = 3 • Final PR = 4	Pilot A 3 1/2
Ability to Set Pitch Attitude	• Low static margin and low damping • Requires 100% of pilot's attention • Statically unstable for α over 10 deg	Pilot A 6 1/2 Pilot B 9	• Lightly damped • Trim mandatory during float • If rating trim problem PR = 5	Pilot A 4
Ability to Track Glideslope	• Impossible		• Pitch attitude is limiting factor	Pilot A 4

he felt that the longitudinal and lateral control power became unacceptably low which made the vehicle a 7 or 8. Pilot A spent considerably more time flying the vehicle and was able to make a more detailed evaluation (see Table 12). In addition to the ratings given in Table 12, Pilot A indicated that his overall lateral rating was a 3 1/2 and longitudinally a 4 1/2.

SECTION IV

SUMMARY AND RECOMMENDATIONS

It was found that large portions of the military handling qualities specification (8785B) are directly applicable to the Orbiter. However, there are several areas where additional or substitute criteria are necessary and modifications are recommended, the major ones being:

- Additional flight path control criteria for an unpowered orbiter (not covered by 8785B)
- A substitute criterion for the short period characteristics during the final approach and landing
- A criterion to prevent longitudinal pilot-induced oscillations
- A new criterion for adequate heading control
- A substitute criterion for primary flight control system dynamics

The tests of three specific Orbiter designs generally confirmed the ability to anticipate handling quality problems by applying the criteria of 8785B and the recommended revisions.

During the course of this project, two potentially troublesome design problems were encountered. One is due to the large pitch trim changes required for an unpowered Orbiter during the final approach or float phase. A good trim system is essential for satisfactory manual control. The other problem relates more to ride, rather than handling, qualities. With a large aircraft at a high angle of attack (the Orbiter near touchdown) the automatic coordination of turn entries can cause excessive lateral accelerations at the cockpit. The design trade-offs between the ride, degree of turn coordination, and roll power need to be more fully investigated.

It is strongly recommended that additional research be conducted in these two problem areas. Resolution of these problems is considered essential to the development of a definitive SSV handling qualities specification.

Additional research in the area of flight path control criteria is also considered essential because of the potential impact of the criteria on basic vehicle parameters and trajectory limitations. If an unpowered Orbiter is selected, the criteria proposed here need to be extended. The effects of IFR flight and the effects of adding a flight director display should be assessed. The potential influence on the criteria of variations in L/D also needs further investigation. If a powered Orbiter is selected, a better flight path control criterion than that of 8785B is definitely needed.

Further research on heading control criteria is also considered important but of lower priority than the subjects noted above. The criterion proposed here appears to be a significant advancement, but additional verification, and possible refinement, is highly desirable.

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APPENDIX A

FLIGHT PATH CONTROL FOR POWERED VEHICLES

It is assumed that during the final approach and landing a powered orbiter would be flown very much like a conventional aircraft of comparable class. Therefore the existing handling quality data on flight path control should be directly applicable. In this appendix we will analytically evaluate the potential importance of several parameters. Then the analytical results will be compared with experimental data from a variety of sources.

We begin by deriving the flight path transfer function (and time response) using the conventional flight path through attitude control structure shown in Fig. A-1. If we assume good attitude dynamics the pilot can close an

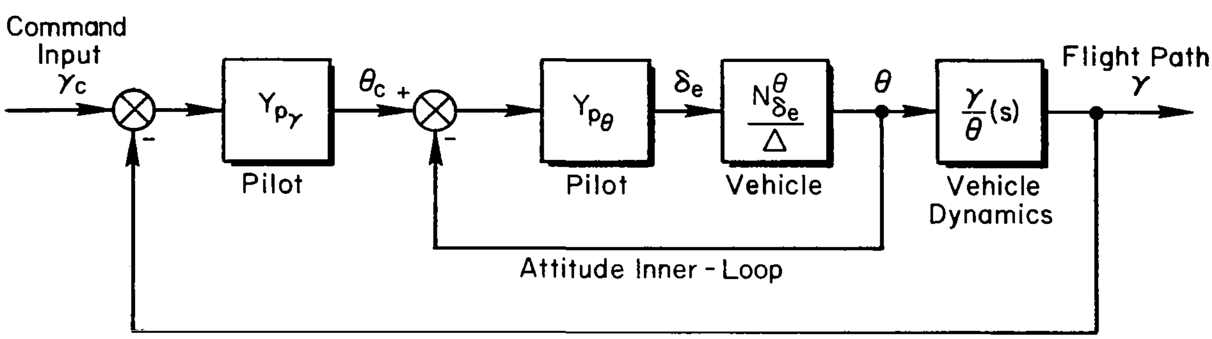

Figure A-1. Flight Path Control Structure

inner attitude loop with the elevator such that $\theta \doteq \theta_c$ for the frequencies (or times) of significance for path control. Then the flight path response to θ_c can be found from the ratios of numerators as follows*

$$\frac{\gamma}{\theta_c} \doteq \frac{N^{\gamma}_{\delta_e}}{N^{\theta}_{\delta_e}} \doteq \frac{s + 1/T_{h_1}}{(s + 1/T_{\theta_1})(T_{\theta_2} s + 1)} \qquad \text{(A-1)}$$

*Assumes $\dot{h} = U_o\gamma$ and trim flight path angle is small.

where:

- $1/T_{h_1}$ is the lowest frequency zero associated with elevator control of altitude. It can be negative or positive, depending, respectively, on whether the approach speed is below or above that for minimum drag. The two additional high frequency zeros are neglected in this approximation.

$$\frac{1}{T_{h_1}} \doteq -g\frac{d\gamma}{dV} \qquad \text{(A-2)}$$

$$\doteq -\frac{1}{3}\frac{d\gamma}{dV} \quad \text{for } d\gamma/dV \text{ in deg/kt}$$

- $1/T_{\theta_1}$ is the lowest frequency zero in the pitch-attitude-to-elevator transfer function.

- $1/T_{\theta_2}$ is the remaining zero in the pitch-attitude-to-elevator transfer function. It characterizes the initial relative motions in altitude and attitude resulting from control with the elevator.

Sample flight path responses to a unit step attitude change are shown in Fig. A-2. The initial response is determined primarily by T_{θ_2}. The

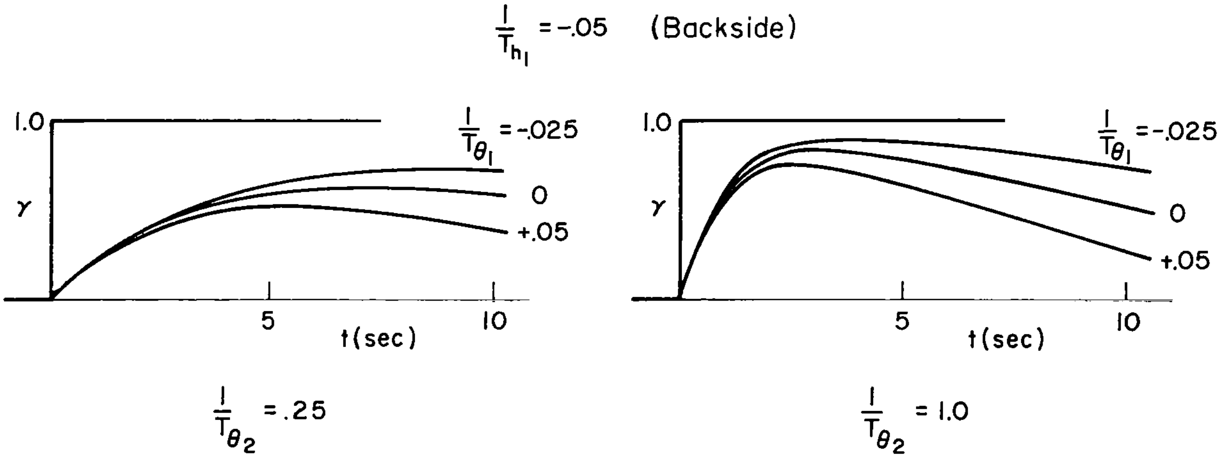

Figure A-2. Sample Flight Path Responses

initial response rate is $1/T_{\theta_2}$. Then as airspeed bleeds off, the flight path angle decays. If $1/T_{\theta_1}$ is positive, the flight path will eventually reach a steady state value of T_{θ_1}/T_{h_1}. The complete expression for the flight path response is given by:

$$\gamma(t) = \underbrace{\frac{T_{\theta_1}}{T_{h_1}}}_{\substack{\text{Steady} \\ \text{State} \\ \text{Value}}} + \underbrace{\frac{\left(1 - \frac{T_{\theta_1}}{T_{h_1}}\right)}{\left(1 - \frac{T_{\theta_2}}{T_{\theta_1}}\right)} e^{-t/T_{\theta_1}}}_{\text{Bleedoff Term}} - \underbrace{\frac{\left(1 - \frac{T_{\theta_2}}{T_{h_1}}\right)}{\left(1 - \frac{T_{\theta_2}}{T_{\theta_1}}\right)} e^{-t/T_{\theta_2}}}_{\substack{\text{Initial Response} \\ \text{Term}}} \qquad \text{(A-3)}$$

Note that although $1/T_{h_1}$ alone is sufficient to indicate a "backside" flight condition, the flight path response is not characterized solely by $1/T_{h_1}$. The steady-state value of γ is a function of the T_{h_1}/T_{θ_1} ratio, and the bleedoff is strongly affected by all three time constants. It would appear that a pilot's acceptance of backside operation therefore could not be determined from the value of $1/T_{h_1}$ alone.

The parameter, $1/T_{\theta_1} - 1/T_{h_1}$, has an especially significant effect on the response. This can be seen in Fig. A-3 where the peak flight path angle for a unit attitude change is shown to be nearly constant for a given value of $(1/T_{\theta_1} - 1/T_{h_1})/(1/T_{\theta_2})$, regardless of the value of the backside parameter $1/T_{h_1}$.

Another important property of $1/T_{\theta_1} - 1/T_{h_1}$ is that it is always positive and approximately proportional to $1/U_o^3$. More specifically:

$$\frac{1}{T_{\theta_1}} - \frac{1}{T_{h_1}} \doteq \frac{gZ_u}{U_o Z_w} \doteq -\frac{2}{Z_w}\left(\frac{g}{U_o}\right)^2$$

This means that handling qualities studies which varied backside gradient by varying derivatives X_u, X_α, or X_{δ_e} at constant speed did not change the value of $1/T_{\theta_1} - 1/T_{h_1}$, i.e., variations in $1/T_{h_1}$ were accompanied by essentially the same variations in $1/T_{\theta_1}$. Consequently, verification of the importance of $1/T_{\theta_1}$ on flight path control can only be accomplished by comparing data from different experiments. These types of correlations

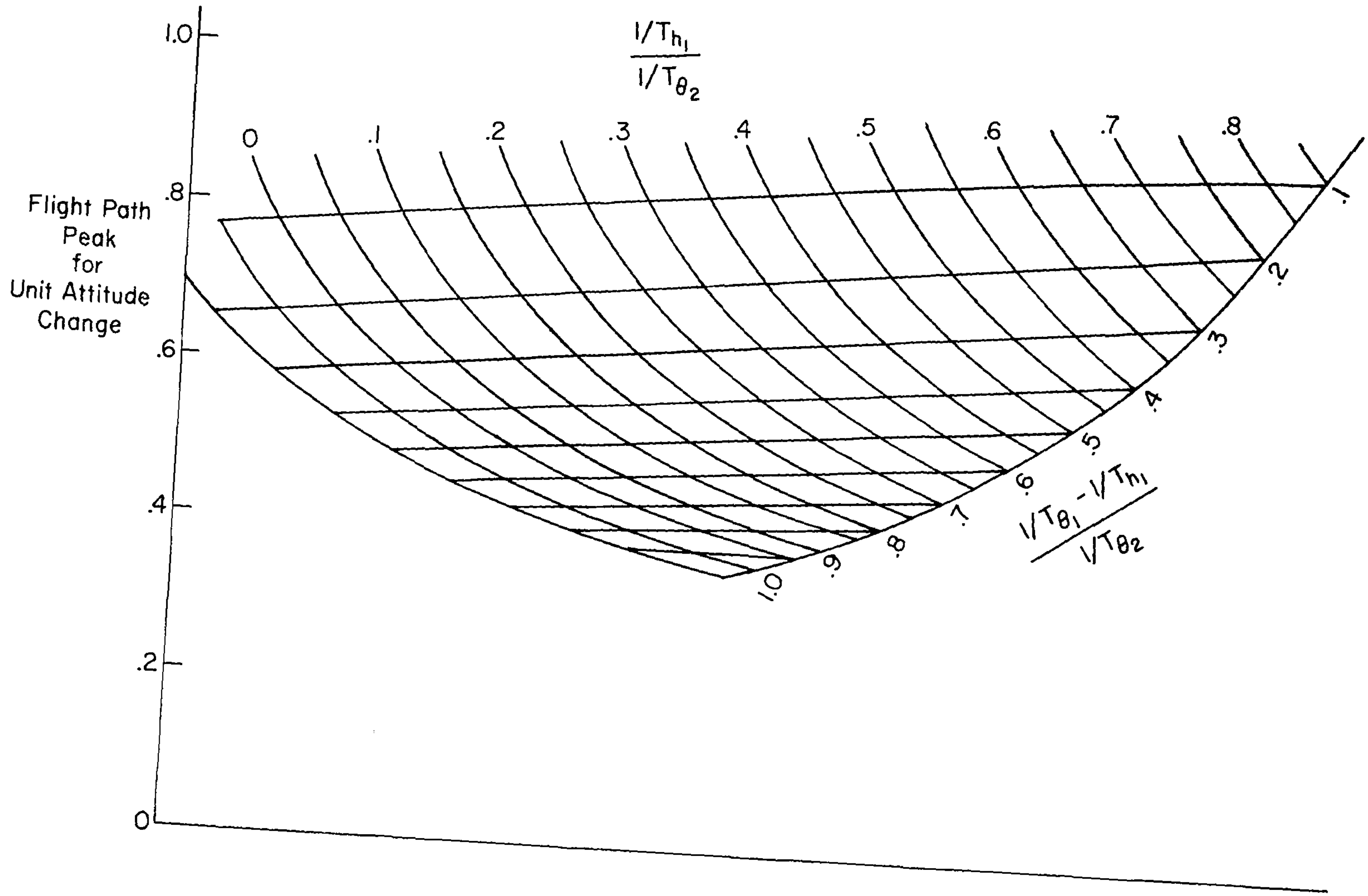

Figure A-3. Peak Flight Path Response

are always difficult because of the great many experimental factors which differ from one test to another. Nevertheless, the comparison was made.

The results of nine handling qualities studies of backside conditions were analyzed. These references are presented in Table A-1 along with the experimental conditions and parameters that may influence the pilot rating results. The attitude dynamics listed in Column 6 represent the best short-period characteristics tested, i.e., those that produced the best rating for a given backside condition. Hopefully, this will normalize the ratings to reflect changes in flight path control only. The changes in phugoid characteristics are not considered significant, but the changes due to thrust lag and T_{θ_2} force a data separation. Considering the data with 0 to 0.5 sec thrust lag and $1/T_{\theta_2}$ from 0.6 to 0.8 separates one group of five experiments. A second group of three tests has thrust lags of 1.5 sec to 2.0 sec with $1/T_{\theta_2}$ from 0.88 to 1.0. Reference A-3 falls in neither group and should have poorer ratings due to both low $1/T_{\theta_2}$ and large thrust lag. An additional report (Ref. A-8) which tested the SST at two backside conditions was not included in Table A-1 because of short-period deficiencies.

The data were initially compared by plotting the experimental variable $1/T_{h_1}$ versus pilot rating as was done in each of the references. This comparison is shown in Fig. A-4. The trend for poorer ratings as $1/T_{h_1}$ is made more negative is apparent, as is the general bias of about one rating point between the data with quick thrust response (open symbols) and the data with 1.5 to 2.0 sec thrust lags (darkened symbols). Although not shown, Ref. A-6 also ran several thrust lag cases at a given backside level and noted a similar rating degradation of one point between 0 sec and 2.0 sec thrust lag. It is interesting to note that this well known effect is not reflected in the 8785B specification.

The data seem fairly consistent except for the AGARD 420 results, which show acceptable ratings for $1/T_{h_1}$ up to −0.25. The validity of this data is questionable for two reasons. First, the altitude information was determined by a ground tracker and radioed to the pilot. Thus the pilot could concentrate on attitude and airspeed. Secondly, the $1/T_{h_1}$ values were augmented by feedbacks to the throttle. Thus the pilot might have had an audio cue of what was about to happen.

TABLE A-1

BACKSIDE DATA SOURCES

DATA SOURCE	SIMULATION	EXPERIMENTAL TASK	EXPERIMENTAL VARIABLES	ENGINE LAG TIME CONSTANT	BEST ATTITUDE DYNAMICS (ζ_{sp} ; ω_{sp})	PHUGOID DYNAMICS (ζ_p ; ω_p)	$1/T_{\theta_2}$
Ref. A-1 AFFDL-TR-66-2 (CAL)	In-flight T-33 at 160 kt	Instrument descent, visual glide slope tracking	$1/T_{h_1}$ ζ_p ; ω_p	$\doteq$ 2 sec	0.45 ; 2.46	> 0 ; 0.15	1.0
Ref. A-2 FDL-TDR-64-60 (CAL)	In-flight T-33 at 160 kt	Same as above	ζ_{sp} ; ω_{sp} $1/T_{h_1}$	$\doteq$ 2 sec	> 0.3 ; 2.0	0.1 ; 0.17	1.0
Ref. A-3 FDL-TDR-64-84 (CAL)	Fixed-base T-33 at 120 kt (smooth air)	Instrument flight pattern (no ILS)	$1/T_{h_1}$ ζ_{sp} ; ω_{sp} $1/T_{\theta_2}$	2 sec	0.5 ; 1.0 0.25 ; 2.0 for $1/T_{h_1} = -0.064$	> 0 ; 0.2	0.5
Ref. A-4 STI-TR-130-1 (STI)	Fixed-base F4D-1 at 120 kt	Carrier landing	$1/T_{h_1}$	0.5 sec	0.31 ; 2.54	$\doteq$ 0.1 ; 0.20	$\doteq$ 0.7
Ref. A-5 NASA TN-D-3971 (LRC)	In-flight Boeing 367-80 for Delta Wing SST at 135 kt	ILS approach and landing	$1/T_{h_1}$	Small	0.8 ; 1.45	0.06 ; 0.126	0.8
Ref. A-6 AFFDL-TR-65-227 (NAA)	Moving-base Delta SST at 135 kt	ILS approach and landing	$1/T_{h_1}$	0	0.58 ; 2.11	0.11 ; 0.17 (varied as $1/T_{h_1}$)	0.6
Ref. A-7 AGARD 420 (RAE)	In-flight AVRO 707A at 120 kt	GCA approach	ζ_p $1/T_{h_1}$	1.5 sec	0.38 ; 1.68	ω_p = 0.18	0.88
Miller* (Princeton)	In-flight NAVION at 95 kt	Visual approaches	$1/T_{h_1}$, $1/T_{\theta_2}$ ω_{sp} τ_{eng}	0.25 sec nominal	0.75 ; 0.90	$\doteq$ 0 ; 0.22	0.60 nominal
Bihrle* (Grumman)	Moving-base fighter at 120 kt (Program X)	Carrier landing	$1/T_{h_1}$, $1/T_{\theta_2}$ ω_{sp}	0.1 sec	0.55 ; 1.0	unknown	0.65

*Unpublished reports, data obtained directly from authors.

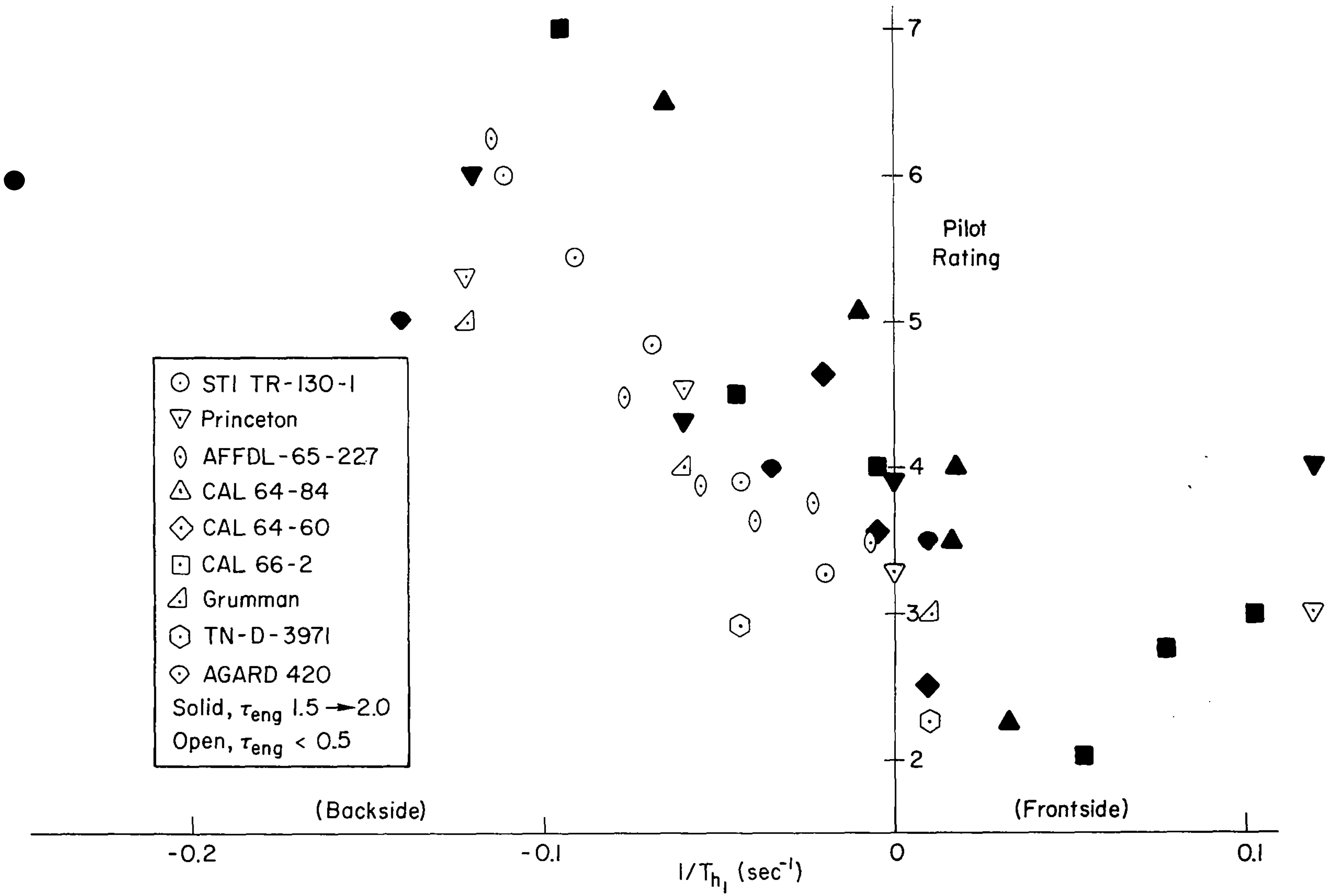

Figure A-4. Pilot Rating Versus $1/T_{h_1}$

With due justification for separating the data into two groups as a function of thrust lag, we can now look at the effect of $1/T_{\theta_1}$. Figure A-5 shows $1/T_{\theta_1}$ plotted versus $1/T_{h_1}$ for three pilot rating categories, i.e., satisfactory, unsatisfactory, and unacceptable. This was obtained by fairing the data of Fig. A-4 and interpolating.

The data of Fig. A-5 indicate that there may be a significant effect of $1/T_{\theta_1}$ on allowable values of $1/T_{h_1}$ (or $d\gamma/dV$). From the analytical results presented above such an interaction would be expected. If it does exist, it should be reflected in a handling quality specification. Unfortunately, the available data do not seem adequate to define a new criterion with a reasonable level of confidence. A special handling quality experiment to conclusively define the effects of $1/T_{\theta_1}$ should be conducted.

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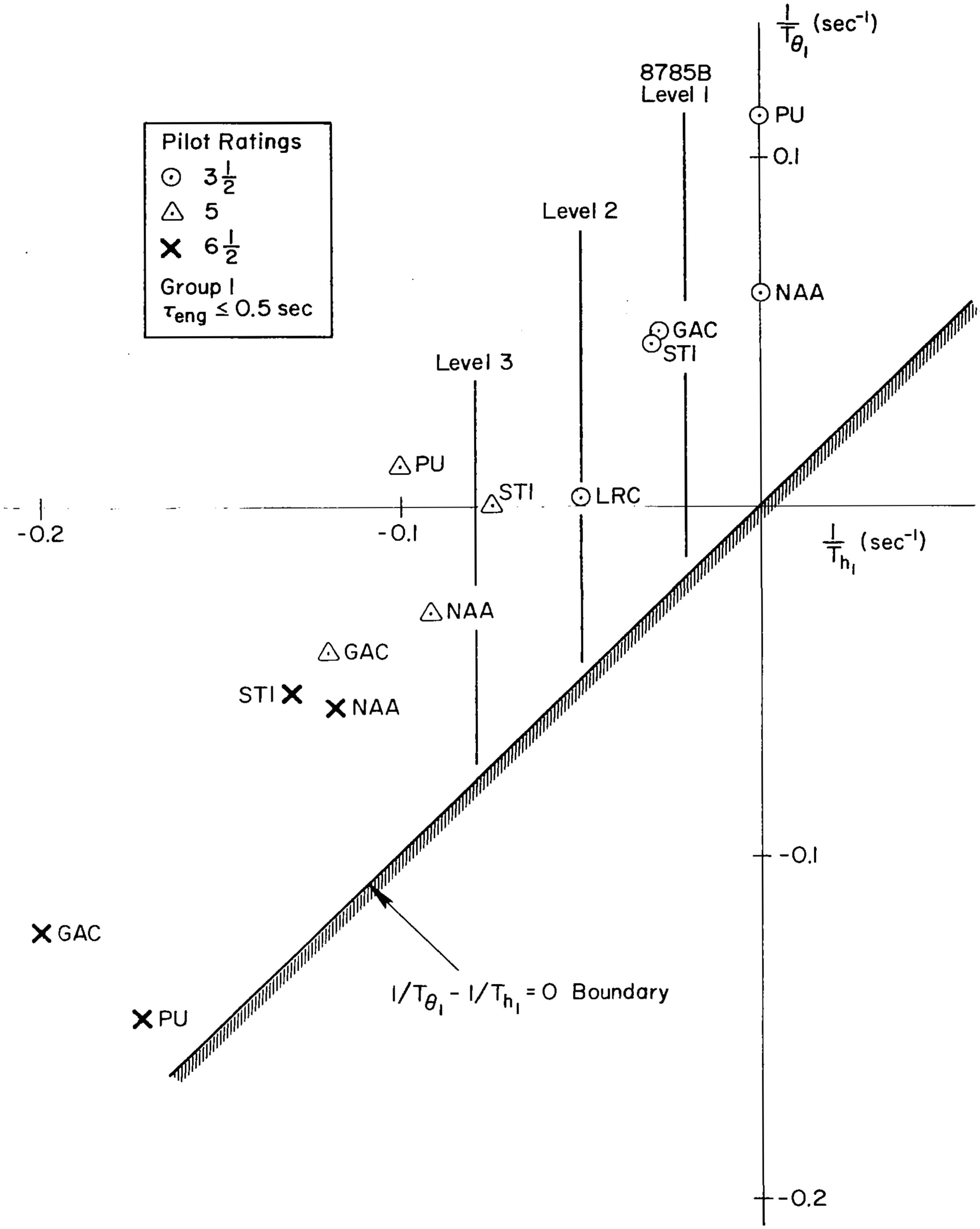

a. Small Thrust Lag

Figure A-5. Effect of $1/T_{\theta_1}$ and $1/T_{h_1}$ on Pilot Ratings

A possible metric is the ratio of L/D to $(L/D)_{max}$, i.e.

$$\frac{L/D}{(L/D)_{max}} \doteq \frac{2QQ_o}{Q^2 + Q_o^2} \tag{B-2}$$

Another, closely related, metric is the possible change in L/D.

$$\Delta(L/D) = (L/D)_{max} - L/D \doteq \frac{(Q - Q_o)^2}{Q^2 + Q_o^2}(L/D)_{max} \tag{B-3}$$

A similar metric is the possible change in flight path angle.

$$\Delta\gamma = \cot^{-1}(L/D) - \cot^{-1}(L/D)_{max} \tag{B-4}$$

$$\doteq \frac{(Q - Q_o)^2}{2QQ_o}\frac{1}{(L/D)_{max}}$$

A fourth metric is the airspeed convergence time constant, T_γ. If a small change in flight path is made, the airspeed will exponentially approach the new equilibrium value. The time constant for the airspeed change can be approximated by:

$$\frac{1}{T_\gamma} \doteq -g\frac{d\gamma}{dV} \doteq \frac{g}{V}\frac{Q^2 - Q_o^2}{QQ_o}\frac{1}{(L/D)_{max}} \tag{B-5}$$

If the time constant is too long, the airspeed will not stabilize at the new equilibrium value after the pilot makes a flight path change. The resultant difficulty in controlling airspeed could present a serious problem.

For the last metric it was postulated that altitude lost during the airspeed transient might be more important than time per se. Thus a convergence altitude, H, was defined as T_γ times the rate of descent, i.e.,

$$H = T_\gamma V \sin(-\gamma) \doteq \frac{V^2}{2g}\frac{Q^2 + Q_o^2}{Q^2 - Q_o^2} \tag{B-6}$$

This last parameter has an interesting property. The first four metrics increase (or decrease) monotonically as speed is increased above that for $(L/D)_{max}$. However, the convergence altitude has a minimum at a speed of approximately 1.44 times the speed for $(L/D)_{max}$.

Having defined the five possible metrics, the values of each were computed for several flight test aircraft, Table B-1. It was hoped that limiting values might be established by comparison with data from experiments on landing low L/D unpowered aircraft. Unfortunately, the data are not sufficient to determine if one of these metrics is the critical parameter. Therefore a simulation program was planned to establish the relative importance of each criterion and limiting values. The effects of speed brake size on limiting values of the most significant criteria were also to be investigated.

The proposed flight path control criteria are functions of the parameters V/V_o (speed to speed for maximum L/D), V_o, and $(L/D)_{max}$ as indicated in Table B-2. Note that with the exception of $\Delta(L/D)$ and $\Delta\gamma$ there is a different functional dependence between each of the metrics and the three parameters V/V_o, V_o, and $(L/D)_{max}$. Thus by separately varying each of the three parameters it should be possible to determine the most important criteria.

The original plan called for testing the fourteen configurations listed in Table B-3. The short period characteristics were held constant at what should be good values, i.e.,

$$\omega_{sp} = 2.0 \text{ rad/sec}$$

$$\zeta_{sp} = 0.7$$

$$1/T_{\theta_2} = 1 \text{ sec}^{-1}$$

The lateral characteristics were also good with

$$1/T_s = 0$$

$$1/T_R = 2 \text{ sec}^{-1}$$

$$\omega_d = 1 \text{ rad/sec}$$

$$\zeta_d = 0.2$$

and aileron characteristics such that turns were well coordinated.

TABLE B-1

COMPARISON OF FRONTSIDE METRICS

AIRCRAFT (REFERENCE)	CONFIGURATION	$\frac{(L/D)}{(L/D)_{max}}$	$\Delta(L/D)$	$\Delta\gamma$ (deg)	$\frac{1}{T_\gamma}$ (sec^{-1})	H (ft)
F-104 (B-2, 3)	Brakes V_{app} = 415 kt	0.50	2	12	0.045	6,600
	Brakes, flap and gear V_{app} = 300 kt	0.75	0.7	6	0.086	3,000
	Gear, Flap V_{app} = 280 kt	0.81	0.75	3	0.032	5,300
F-102 (B-4)	Brakes V_{app} = 200 kt	0.88	0.43	2	0.032	3,100
F-111 (B-1)	72° Sweep Gear Down V_{app} = 270 kt	0.98	0.1	0.4	0.006	18,000
HL-10 (B-5)	V_{app} = 300 kt	0.63	1.3	8.5	0.032	4,900
F5D-1 (B-6)	V_{app} = 235 kt	0.75	1.2	4	0.026	4,200
X-15 (B-7)	V_{app} = 300 kt	0.78	1.0	3.4	0.020	7,000

TABLE B-2. FUNCTIONAL DEPENDENCY OF FRONTSIDE METRICS

METRIC	PRIMARILY FUNCTION OF		
	V/V_o	V_o	$(L/D)_{max}$
Percent L/D: $\frac{(L/D)}{(L/D)_{max}}$	√		
L/D margin: $\Delta(L/D)$	√		√
Flight path margin: $\Delta\gamma$	√		√
Convergence time constant: T_γ	√	√	√
Convergence altitude: H	√	√	

The test was conducted on the NASA ARC S-16 simulator, see Appendix E, using two ARC test pilots as subjects. The basic task was an instrument approach down a glide slope of the same angle as the initial flight path. Atmospheric turbulence and initial position errors provided the task disturbances.

The two subjects flew several of the configurations listed in Table B-3. They agreed there were no handling quality problems per se. If there were any problems they were of a performance nature, i.e., the maneuver capability of the configuration was insufficient to compensate for initial errors. If the pilot was initially far short of the desired trajectory, he would pull up to the speed for $(L/D)_{max}$. He would hold that airspeed until he intersected the desired glide slope and then push over to fly down the glide slope. The pilots never had any difficulty holding the airspeed at that for $(L/D)_{max}$.

The above results should simplify the problem of determining how far on the front side to make the initial approach. Since there are no handling quality problems relative to flight path control, the initial approach can be set on the basis of performance requirements. The initial approach should be far enough on the front side so that it is possible to correct for off-nominal conditions, e.g., initial condition errors and wind variations. However, for pilot acceptability, there is an upper limit on the steepness of the approach, see Section II-A and Appendix C.

TABLE B-3. TEST CONFIGURATIONS

CASES	1			2				3			4			
	A	B	C	A	B	C	D	A	B	C	A	B	C	D
V_o (ft/sec)	200	→	→	300	→	→	→	300	→	→	400	→	→	→
V/V_o	1.1	1.5	2.0	1.1	1.5	2.0	1.0	1.1	1.5	2.0	1.1	1.5	2.0	1.0
$(L/D)_{max}$	4.0	→	→	4.0	→	→	→	8.0	→	→	4.0	→	→	→
$L'_r(sec^{-1})$	.5092	.6852	1.164	.5092	.6852	1.1640	.4990	.2564	.3382	.5260	.5092	.6852	1.1640	.4990
$N'_p(sec^{-1})$	.1405	.1015	.0695	.0945	.0677	0.0461	.1040	.0967	.0706	.0518	.0710	.0508	.0346	.0781
$N'_r(sec^{-1})$	−.0358	−.0348	−.0354	−.0241	−.0232	−.0268	−.0295	−.0124	−.0119	−.0136	−.0181	−.0174	−.0201	−.0195

Note: L'_r, N'_p, and N'_r were varied to keep aileron-only turns coordinated.

Longitudinal Constants

$Z_w = -1.0\ sec^{-1}$

$M_\alpha = -2.2\ sec^{-2}$

$M_q = -1.8\ sec^{-1}$

M_{δ_e} = set by pilot

$Z_{\delta_e}, X_{\delta_e}, M_u = 0$

Lateral Constants

$Y_v = -0.40\ sec^{-1}$

$L'_\beta = -1.00\ sec^{-2}$

$L'_p = -2.00\ sec^{-1}$

$N'_\beta = 1.00\ sec^{-1}$

$N'_{\delta_a} = 0$

L'_{δ_a} = set by pilot

N'_{δ_r} = set by pilot

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APPENDIX C

UNPOWERED FLIGHT PATH CONTROL — FLARE, FLOAT, AND TOUCHDOWN

This appendix describes two simulation experiments which investigated handling quality problems during the flare, float, and touchdown phases of the approach. Both tests used the Redifon visual display for altitudes below the Redifon limits (see Appendix E). The float and touchdown phases were always done VFR but for some configurations it was necessary to start the initial flare under IFR conditions. The subjects were always informed of the correct altitude to start the initial flare and the proper flare load factor. Raw ILS information was displayed on the Electronic Attitude Director Indicator, EADI. The simulated glideslope was set for a 3 deg float trajectory.

The first test was designed to answer the following questions*:

- What are the limits on float time and are these limits functions of $(L/D)_{max}$, speed for $(L/D)_{max}$, and flight path response characteristics?
- With proper stick sensitivity or nonlinear stick/elevator gearing can satisfactory landings be made at speeds much less than that for $(L/D)_{max}$?

The basic experimental matrix was based on combinations of the following parameters:

$(L/D)_{max}$	4, 7
Speed for $(L/D)_{max}$	150, 180, 220 kt
Float time	5, 10, 20, 30 sec
Z_w†	−0.5, −1.0 sec^{-1}

The Z_w variations were to change the basic flight path response characteristics, i.e.,

$$\frac{\gamma}{\theta} \doteq \frac{1}{T_{\theta_2}s + 1} \quad ; \quad \frac{1}{T_{\theta_2}} \doteq -Z_w \qquad \text{(C-1)}$$

*In both experiments a parabolic drag versus lift curve was used. The L/D characteristics were changed by variations in $(L/D)_{max}$ and the speed for $(L/D)_{max}$, V_o.

†Z_w varied linearly with airspeed. The cited values are for 180 kt, the nominal speed over the runway threshold.

The short period characteristics were held approximately constant (there were some variations due to changing Z_w). The short period characteristics were:

$$\omega_{sp} \doteq 2.0 - 2.5 \text{ rad/sec}$$
$$\zeta_{sp} \doteq 0.50 - 0.70 \qquad \text{(C-2)}$$

The lateral characteristics were also held essentially constant.

$$1/T_S \doteq 0$$
$$1/T_R \doteq 2 \text{ sec}^{-1}$$
$$\omega_d \doteq 2 \text{ rad/sec}$$
$$\zeta_d \doteq 0.25$$

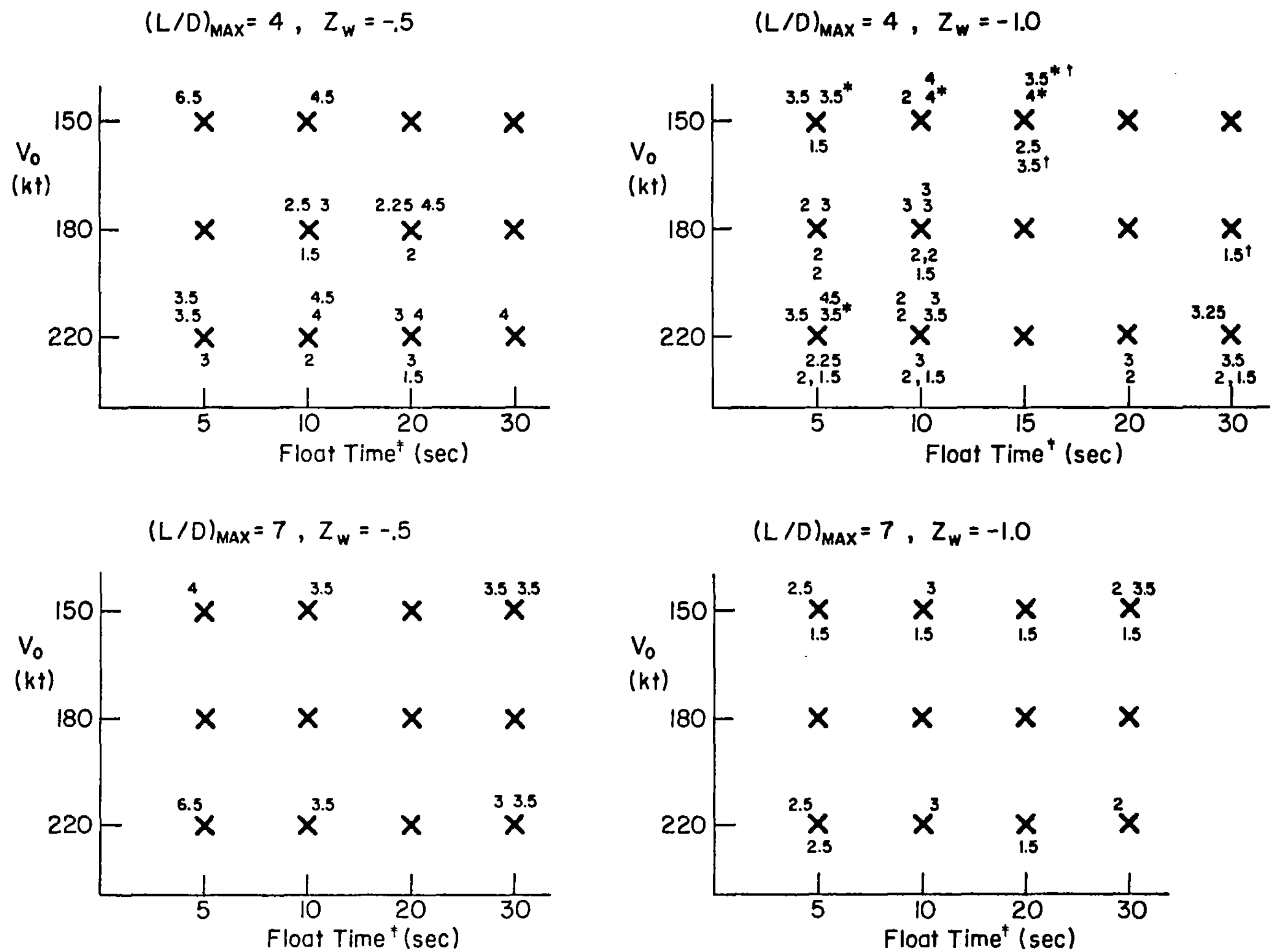
The aileron characteristics were set to provide well coordinated turns, aileron alone.

The initial conditions for each configuration were selected to produce the desired float time with an airspeed of 180 kt over the runway threshold. For those configurations landing below the speed for $(L/D)_{max}$, the effects of nonlinear stick/elevator gearing were investigated. This allowed the pilots to make the rapid pitch changes required as the aircraft decelerated below the speed for $(L/D)_{max}$. The required pitch rates also varied with the value of Z_w.

The test was conducted on the NASA ARC S-16 simulator, Appendix E, with three ARC test pilots as subjects. A summary of the pilot rating results is presented in Fig. C-1. (Note, not all combinations of parameters were tested.) The columns represent different float times and the rows represent the three speeds for $(L/D)_{max}$ tested. The two values of $(L/D)_{max}$ and Z_w correspond to the four quadrants as noted. Pilot ratings (and repeat trials) for the three pilot subjects are presented around the test configurations.

Examination of the pilot ratings allows some general conclusions to be drawn. These include the following:

- High L/D and high Z_w are preferred. Pilot comments indicate this is due to the reduced rate of descent and reduced pitch rate required to flare.



Note: * Redifon visual scene scale at 900:1 instead of 1200:1 (See Appendix E)
† 1 g flare instead of 1/2 g
‡ Float time is from end of flare to runway threshold

Figure C-1. Summary of Pilot Ratings

- High V_o seems preferred except for the PR 6.5 in the lower left-hand corner. Pilot comment about this case indicated the rating was based on the initial flare being too late (unrealistic). Note, in all cases the speed at the threshold was 180 kts.

- Landing well on the backside of the drag curve was quite satisfactory if the pilot had adequate pitch control. For V_o = 220 kt, the pilot was 40 kt on the backside as he came over the threshold.

- The value of Z_w seems to affect pilot acceptance of the very short float times. This would be expected since Z_w controls the flight path response lag, see Eq. C-1.

Pilot comments proved invaluable for evaluating the differences in test cases when the ratings did not reflect any differences. This was primarily due to different portions of the landing maneuver becoming most critical. For example low L/D, low V_o accentuated the steepness of the initial approach and pitch rates required to flare, whereas a high V_o, low Z_w configuration presented problems in the final float and touchdown portion.

Three of the four program variables also produced different quantitative results at touchdown. Going from the most significant to least significant variable in producing differences in the touchdown data are the following:

- $(L/D)_{max}$ — Regardless of the other variables, higher $(L/D)_{max}$ values resulted in longer touchdown distance ($\doteq$ 1000 ft), lower touchdown sink rates ($\doteq$ 3 fps), and somewhat higher touchdown speeds.

- V_o — Regardless of the other variables, a higher V_o tends to produce slower touchdown speeds and longer distances.

- Z_w — The lower Z_w configuration resulted in shorter touchdown distances ($\doteq$ 500 ft), higher touchdown speeds (5-10 kts), and higher touchdown sink rates ($\doteq$ 1 fps).

- Float time — This variable had no independent effect.

Inspection of data taken at the threshold did not produce any consistent trends. It was noted, however, that the threshold speeds turned out to be within 1 kt of the desired 180 kt value without any speed brake manipulation. Thus conditions at the runway are dictated by the initial conditions and are insensitive to variations in pilot technique.

In addition to pilot ratings and quantitative data for the individual configurations, there were several overall factors uncovered in the program that may influence the assessment of the variables and the task. These included:

- VFR versus IFR flare. The visual display has a maximum ceiling of 1200 ft at 900:1 scale. When the configuration had a flare height below this value the task was simplified.
- Elevator sensitivity and trim harmony. Due to the large speed excursions, the trim wheel became a primary controller. Nonlinear elevator gearing with stick deflection received improved pilot ratings in some configurations.
- Flare height and pullout g. It should not be necessary to require a 0.5 g pullout when it produces a very low flare height. On the other hand, a higher g pullout may be necessary to produce an acceptable flight path rate of change.
- Turbulence and wind shears. Without winds there was no need to use the speedbrakes. Winds were not used however because the simulation model, which involved large vertical gusts all the way to touchdown, was unacceptable to the pilots.
- Redifon visual display limitations (see Appendix E). Some configurations could not be evaluated because the rate of descent exceeded the Redifon capabilities.

While the results of the first simulation were very enlightening, the data were not sufficient to establish definite criteria. Therefore a second test was planned to provide additional data. The specific objectives of the second experiment included:

- Determination of how well pilot objections for a specific $(L/D)_{max}$, V_o, Z_w, and float time can be overcome by changes in the flare load factor and the pitch control characteristics (e.g., trim and stick sensitivities and nonlinear stick/elevator gearing).
- Preliminary evaluations of the sensitivity of the flight path criteria to the short period characteristics.
- Investigation of the factors which may limit the touchdown speed — visibility, stick travel, pitch rate, and V/V_o.

- Determination of limiting values for the factors which limit approach speeds — float time, flare altitude, flare load factor, and initial rate of descent.

The first portion of this experiment was devoted to selecting a reasonably good set of pitch attitude control characteristics. This was done to separate the effects of attitude control from those of the other parameters. A basic pitch control problem existed because the substantial decrease in speed that occurred during the final 3° glide resulted in sizable elevator trim requirements. Because of the light force gradient of the sidearm controller used, the high stick forces that normally provide trim cues to the pilot were not available. In addition, the trim control was a thumb wheel which provided direct control over elevator position instead of the usual trim rate "beeper" found on almost all large aircraft. Finally, the trim control was directly connected to the elevator (series trim) making it necessary for the pilot to reposition the stick to neutral when trimming. Because of these factors, the trim task was found to be moderately objectionable to the pilots.

To effectively isolate the attitude control task from other test variables, a rate command plus attitude hold system was developed. The primary advantage of this system was the elimination of trim difficulties during the approach. Trim changes could be made by periodically pulsing the stick. A block diagram of the system is shown in Fig. C-2, below. The net result is that the pitch attitude/stick transfer function is approximately K/s plus a second order lag at about 18 rad/sec with a damping ratio of about 0.5.

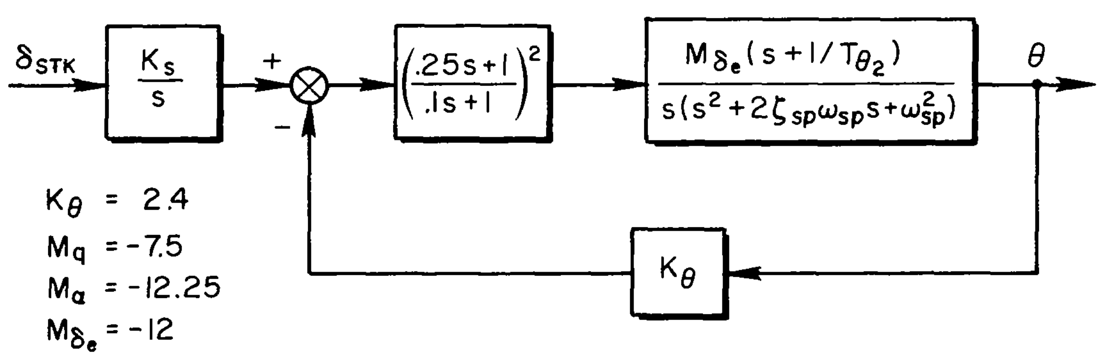


Figure C-2. Rate Command, Attitude Hold System

The pilots rated this system better than either of the "idealized" bare airframe dynamics given for comparison.* For this reason it was decided to use the rate command, attitude hold system for the float time and the attitude to flight path lag ($1/T_{\theta_2}$) tests. However, it should be noted that two fundamental drawbacks of this type system were pointed out by the pilots. These were:

- Neutral speed stability (stick force per knot = 0) — This problem was most evident during flare and touchdown during initial trials with the system. As the pilots gained experience, this problem seemed to have little or no effect on the ratings.
- Continuous operation of the sidearm controller about neutral meant that the pilot was always in the breakout region. This was found to be objectionable to the subject pilots and prevented them from rating the overall attitude system better than fair (PR = 3). It should be pointed out that previous efforts to optimize controller breakout and deadband were not tailored to the present type system.

The next portion of the experiment was an investigation of float time limitations. From numerous pilot comments and ratings from the previous simulation period, it had become obvious that float time limitations are more related to uncomfortable and/or unsafe attitude, altitude, and airspeed combinations than to pilot/vehicle dynamics. For this reason a Situation Rating Scale (more aptly renamed by the pilots as "pucker factor") was devised as follows.

DESCRIPTION	PILOT SITUATION RATING
Acceptable for normal operation with passengers and "average" line pilots	1
Marginal for normal operation. Unsafe under abnormal or emergency conditions	2
Not acceptable for <u>normal</u> operation	3

*The two systems used for comparison were ω_{sp} = 2 rad/sec, ζ_{sp} = 0.5 and ω_{sp} = 4 rad/sec, ζ_{sp} = 1.0.

The primary objective of evaluating the final float phase (3° glide) was to determine the upper and lower boundaries on float time as a function of speed for $(L/D)_{max}$ and $(L/D)_{max}$. As would be expected, the pilots all indicated that the upper boundary on float time per se is essentially nonexistent (the longer the better). However, long float times require considerable initial energy which translates to steep initial flight path angles prior to the first flare. The pilots' preference for low initial flight path angle is clearly illustrated in Fig. C-3.* Pilot comments indicated that the large pitch attitude change required to flare from high flight paths to a 3° glide was unacceptable for normal operation of a shuttle type vehicle. For both pilots the situation rating versus initial descent angle has a sharp increase at an angle of about 20 deg.

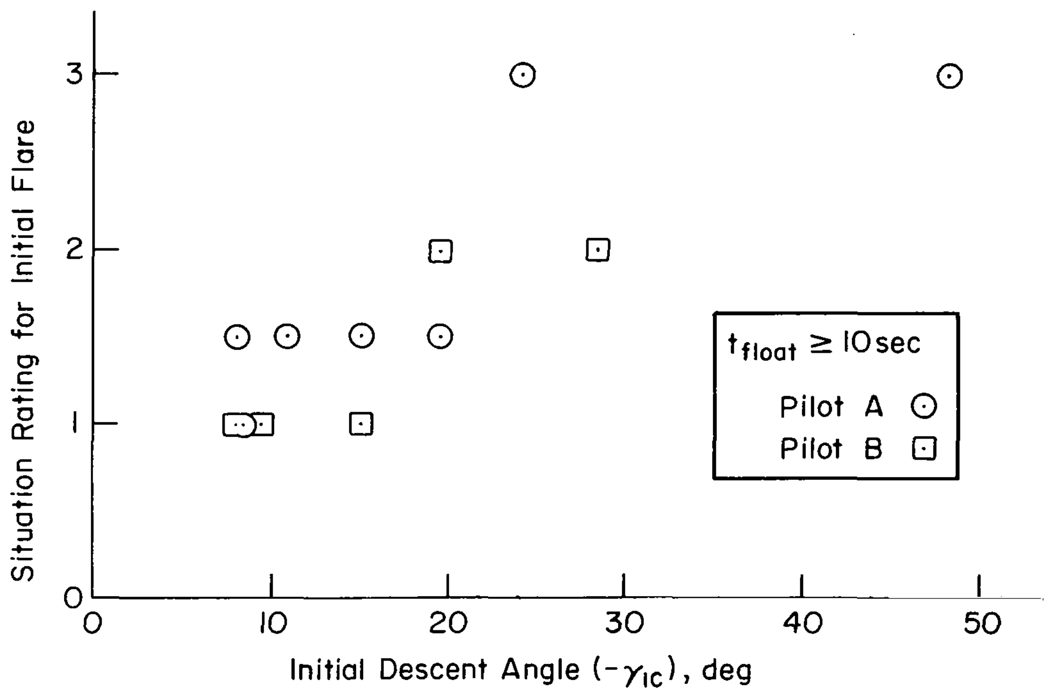


Figure C-3. Effects of Initial Descent Angle

*The complete set of situation ratings are given in Table C-1 and the initial conditions in Table C-2.

TABLE C-1

SUMMARY OF SITUATION RATING DATA FOR FLOAT TIME EXPERIMENT

$(L/D)_{max}$	4		7		4		7	
V_o – kts	150		150		220		220	
T_{float}–sec	PILOT A	PILOT B	PILOT A	PILOT B	PILOT A	PILOT B	PILOT A	PILOT B
2	hit Redifon visual scene vertical rate limit					1.75, 2, 2	1.5, 2, 1	2.25, 2, 1.75
5					3, 3, 3	1.5, 1, 1.5		
10	3, 2, 1				–, 2, 2		1.5, 1.5, 1	1, 1, 1
20	3, –, –		1.5, 1, 1					
30			1.5, 1, 1	1, 1, 1	1.5, –, –	2, 1, 1	1, 1, 1	1, 1, 1
40						2, 1, 1.5		
50								1, 1, 1

NOTES: (1) Cooper Harper Rating = 3.5 for all t_{float} (i.e., aircraft dynamics did not change with t_{float}.

(2) $1/T_{\theta_2} = 0.5$ at V = 180 kt.

(3) The three situation ratings are for initial flare, float, and final flare and touchdown.

(4) – indicates no rating was given for that particular phase of the trajectory.

TABLE C-2

INITIAL AND FLARE CONDITIONS

t_{float} (sec)	10	20	20	30	2	5	10	30	40	2	10	30	50
V_o (kt)	150	150	150	150	220	220	220	220	220	220	220	220	220
V_{ic} (kt)	262	370	231	277	217	229	241	336	424	323	347	406	471
$(L/D)_{max}$	4	4	7	7	4	4	4	4	4	7	7	7	7
h_{ic} (ft)	3000	8770	1380	2727	1441	1570	1550	3640	7923	705	840	1391	2111
h_{flare} (ft)	1210	4120	600	1509	551	630	540	1750	4505	230	350	808	1371
γ_{ic} (deg)	−23.9	−48.2	−11.4	−15.1	−14	−14.1	−14.3	−19.4	−28.5	−8.4	−8.2	−8.3	−9.1
Δn_z flare	.5	1.0	.5	.25	.25	.25	.50	.50	.50	.25	.25	.25	.25

The lower boundary on float time is best illustrated by plotting the pilot situation ratings versus float time as shown in Fig. C-4. Pilot comments reveal that the degradation in ratings for low float time is due to the lack of time available to get set up for final flare and touchdown. Overall, the lower limit on float time seems to be about 10-15 sec, which agrees with the low L/D flight experience. However, as noted earlier the minimum float time appears to be dependent on the value of $1/T_{\theta_2}$. Since T_{θ_2} is the lag time constant between pitch attitude and flight path angle, Eq. C-1, it seems reasonable for the minimum float time to be roughly proportional to T_{θ_2}. The limit of 10-15 sec for T_{θ_2} equal to 2 sec corresponds to a float of 5-7.5 time constants. This is a reasonable interval to allow for flare/float transients to decay.

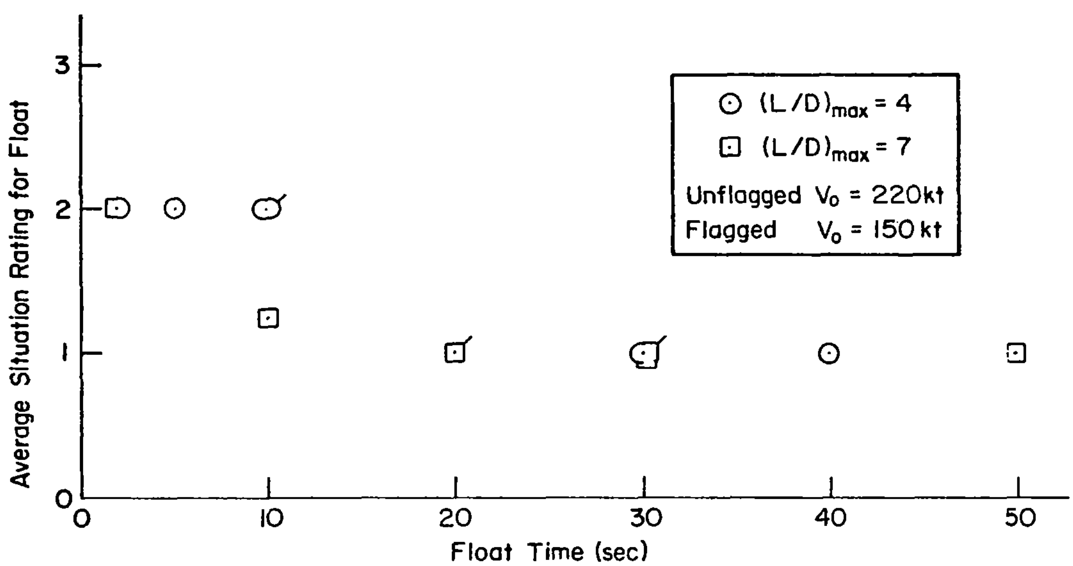


Figure C-4. Effects of Float Time

The next portion of this experiment was to vary $1/T_{\theta_2}$ at a constant float time of 30 sec. The pilot rating data are listed in Table C-3 and plotted in Fig. C-5. A summary of the pilot comments relating to the

TABLE C-3

PILOT RATING SUMMARY FOR $1/T_{\theta_2}$ VARIATIONS

	SITUATION RATING				COOPER-HARPER RATING			
$(L/D)_{max}$	4		7		4		7	
$1/T_{\theta_2}$	PILOT A	PILOT B	PILOT A	PILOT B	PILOT A	PILOT B	PILOT A	PILOT B
0.25	3, –, 3	2.25, 1, 3	1, 1, 1	1, 1, 1	5, 5, 6.5	5.5, 3, 8.5	3.5, 3.5, 3.5	3.5, 4.5, 6.75
0.5	2, –, 2	2, 1, 1.5	1, 1, 1	1, 1, 1	3.5, 3.5, 5	4.5, 3, 3.25	3, 3, 3.5	2.5, 2.5, 2.5
1.0	1.5, –, 1.5	1, 1, 1			3.5, 3.5, 3.5	3, 2.5, 2.75		
2.0	1.5, –, 1	1, 1, 1	1, 1, 1	1, 1, 1	3.5, 3.5, 4	3.5, 2.75, 4.5	3, 3, 4.5	2.5, 3.5, 4.5

NOTES:
(1) Values of $1/T_{\theta_2}$ given are for V = 180 kt.

(2) V_o = 220 kt.

(3) t_{float} = 30 sec.

(4) The three ratings are for initial flare, float, and final flare and touchdown.

(5) – indicates no rating was given for that particular phase of the trajectory.

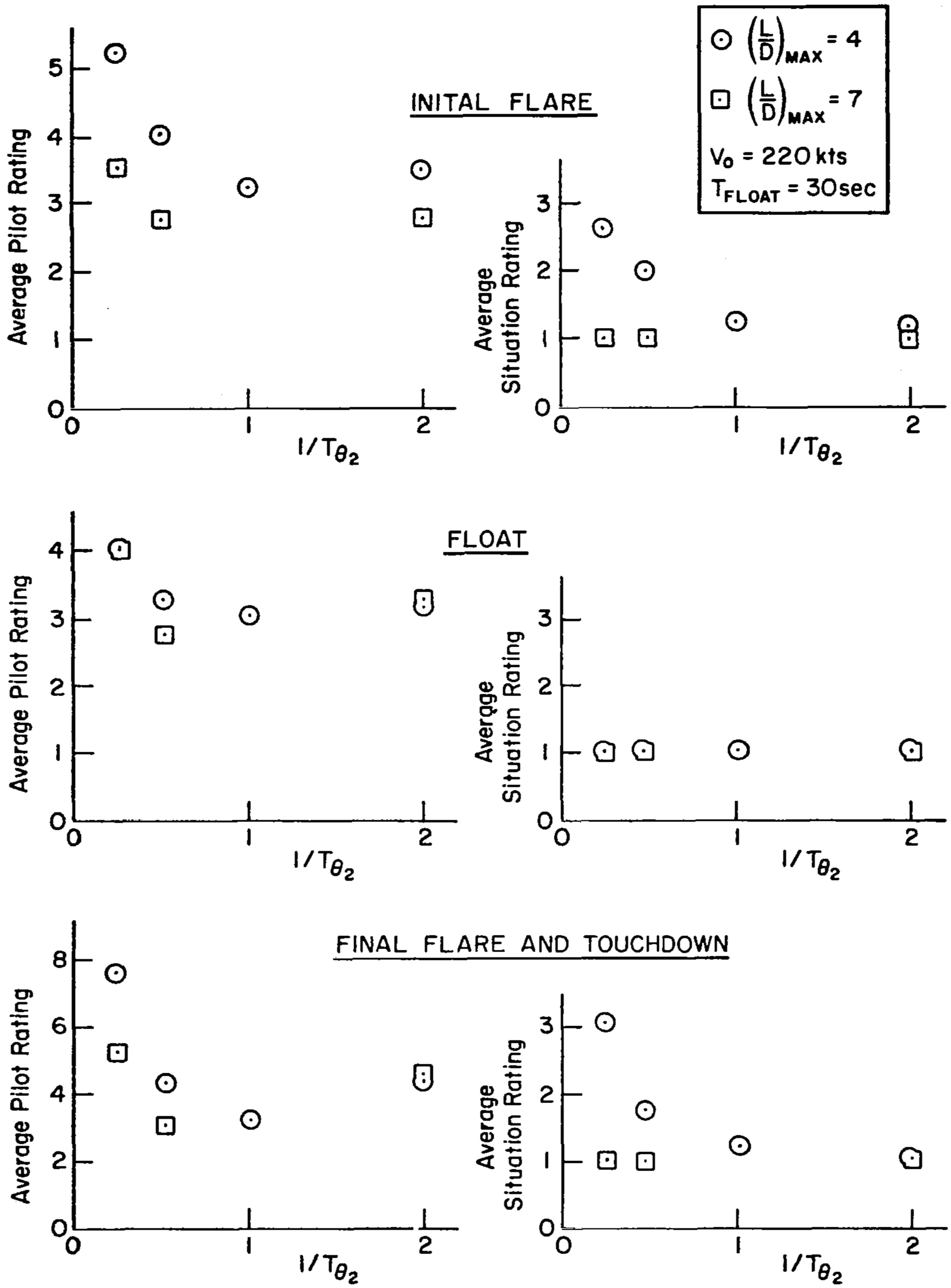


Figure C-5. Pilot Rating Data

ratings for low $1/T_{\theta_2}$ is given below.

	INITIAL FLARE	FLOAT	FINAL FLARE AND TOUCHDOWN
SITUATION RATING	Large attitude maneuvers for low L/D No problem — high L/D	No problem	Poor visibility over nose due to high attitude — Low L/D No problem — High L/D
HANDLING QUALITIES RATING (COOPER-HARPER)	Tend to overshoot glideslope during capture — hard to set attitude for float — low L/D sluggish — high L/D	Large attitude changes required to track — objectionable hunting and stick pumping	Large pitch rate required at touchdown. Bottom drops out

The degradation in pilot rating for high $1/T_{\theta_2}$ (final flare and touchdown) was due to a tendency to balloon and float when attempting to touchdown on a predetermined spot on the runway. This may be due to a combination of high attitude/flight path sensitivity and inadequate visual cues due to inherent limitations of the Redifon display.

The above data may appear to indicate an effect of L/D on the minimum $1/T_{\theta_2}$. However, on closer examination and comparison with the data of Ref. C-1 the effect of L/D becomes questionable. Consider the following factors:

1. The initial flare ratings for the lower L/D case are somewhat degraded because of the steep initial descent angle, 19 deg.

2. There is negligible effect of L/D on the float ratings.

3. The effect of L/D on situation rating for final flare and touchdown is due to visibility problems which are not of direct concern here.

4. The effect of L/D on handling quality ratings for final flare and touchdown is due to problems in pitching the aircraft rapidly enough to compensate for the speed decay. In a similar experiment, Ref. C-1 reported satisfactory ratings (PR < 3.5) for an $(L/D)_{max}$ of 3 and

$1/T_{\theta_2}$ of about 0.35 sec⁻¹. Since the Ref. C-1 test used a center stick with a trim rate switch, it appears that pitch controller characteristics can strongly affect this phase of the landing.

At this point we must conclude there is a lower limit on $1/T_{\theta_2}$ (roughly 0.4 for the approach speeds used here), but a possible effect of L/D cannot be defined.

The final portion of this experiment consisted of variations in short period dynamics (the rate command, attitude hold system was removed). The objective was to obtain a preliminary estimate of the validity of the 8785B and Section II-B short period boundaries when applied to the shuttle approach and landing. An unique feature of the shuttle is the rapid decrease in speed during the final 3° glide which results in a corresponding decrease in short period frequency.* This test was designed so that the short period roots remained within the criterion boundary for some cases, and in other cases the roots were allowed to cross the boundary at some point during the approach, see Fig. C-6 and C-7. The symbols shown on Figs. C-6 and C-7 (for two values of L/D) designate the location of the short period roots at the beginning and end of each run. In all cases the Situation Ratings were good, so poor pilot ratings should be due only to short period characteristics. The pilots were asked to give a separate rating for glideslope intercept and tracking and for final flare and touchdown. It was expected that the final flare and touchdown ratings would be significantly degraded because of the low short period frequency at the end of the run. This was not the case, however, and very little or no rating difference was given for the two tasks for all configurations tested.

The trim problem discussed earlier is believed to have been a major factor in the unexpectedly poor ratings given for Case 3. This conclusion is based on the fact that the pilot comments indicated PIO and trim problems and that investigation of the analog records indicate nearly identical PIO type time histories for Cases 3 and 4. Since Case 3 is rated much worse than 4, and 4 requires very little trim, it appears that trim is the deciding factor.

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*ω_{sp} varies nearly linearly with speed, and ζ_{sp} is nearly independent of speed.

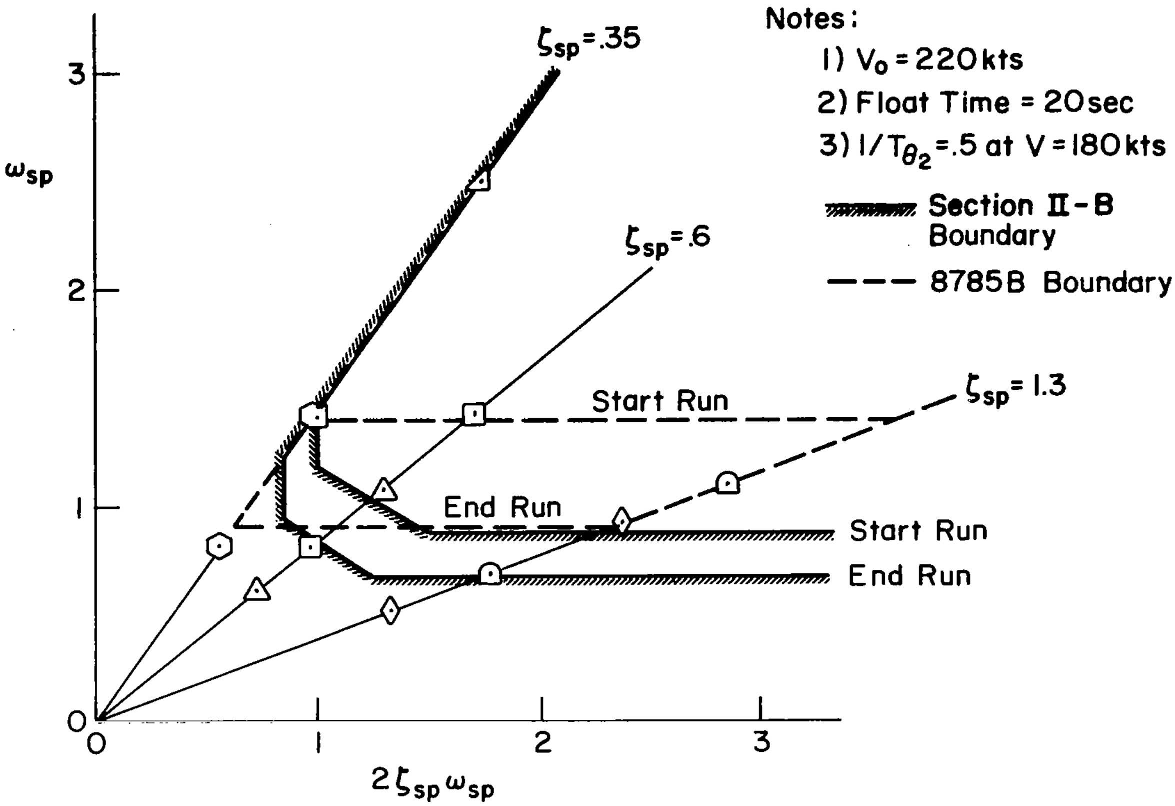
Because of the sizable pilot to pilot variation in ratings it is impossible to draw any conclusions regarding the validity of the existing short period boundaries. However, the following observations are of interest.

- Decreasing the $(L/D)_{max}$ does seem to degrade the ratings when the short period damping is minimum. ($\zeta_{sp} = 0.35$)
- For a given pilot, there is very little change in the ratings when crossing the criteria boundaries.

It should be noted that Pilot A felt that tracking on ILS beam without a flight director display can never be better than a pilot rating of 3 1/2 regardless of the vehicle dynamics or control system. This might explain some of the variation between pilots.

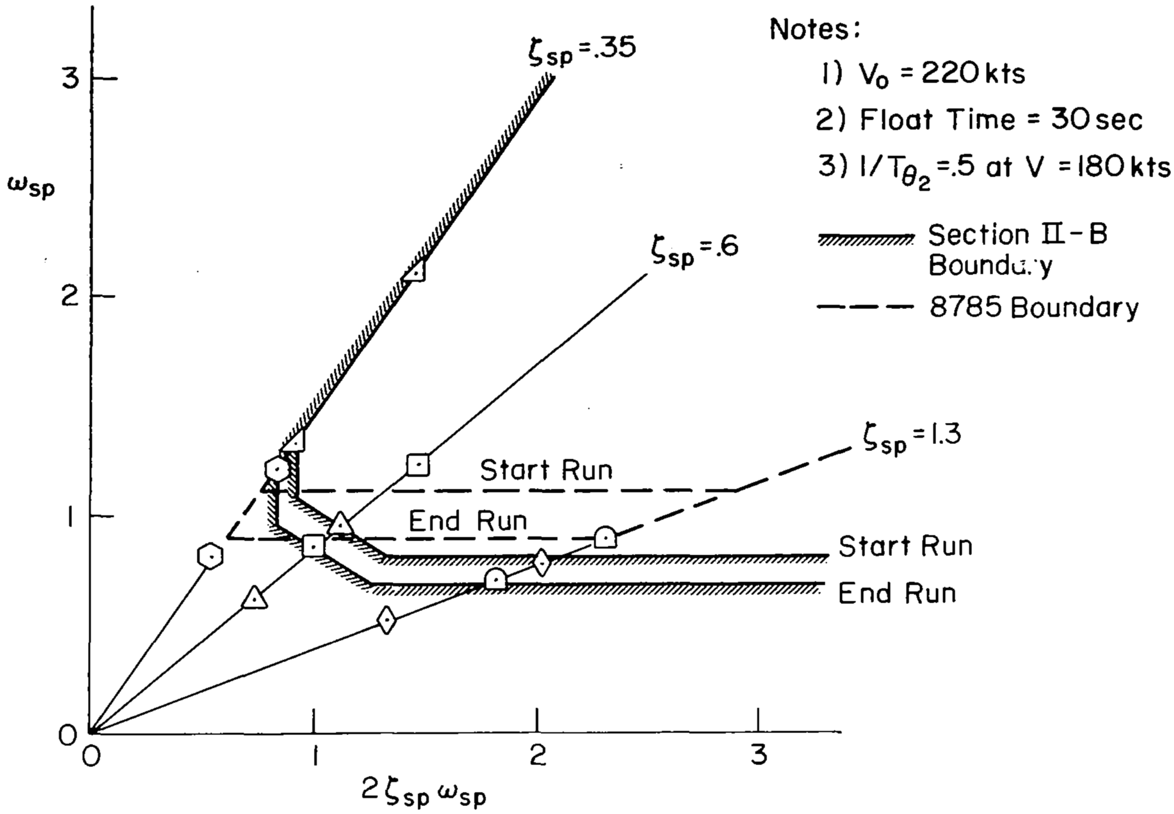
REFERENCES

C-1. Bonine, W. J., Horizontal Landing Study. Phase I. Preferred Approach Conditions for Low L/D Glide Vehicles Utilizing a High Energy Approach Technique, McDonnell Aircraft Corp. Rept. G172, 5 Apr. 1968.



		PILOT A		
CASE	SYMBOL	INITIAL	FINAL	PILOT COMMENTS
1	⊡			
2	△	4 1/2	4 1/2	Feels lightly damped — desirable to trim
3	◿	6 1/2	6 1/2	Trim problem quite severe. Worse than $(L/D)_{max} = 7$
4	⬡	4 1/2	4 1/2	Little goosy — would like more damping
5	⌂			
6	◊	5	5	Takes nose down stick at touchdown — things happen faster than at $(L/D)_{max} = 7$

Figure C-6. Variation of Short Period Roots $(L/D)_{max} = 4$



		PILOT A		PILOT B		
CASE	SYMBOL	INITIAL	FINAL	INITIAL	FINAL	PILOT COMMENTS
1	⊡	4 1/2	4 1/2	2	2 1/2	Little loose in attitude — desirable to trim
2	△	5	5	3 1/4	2 1/2	Not enough damping. Have to push attitude around
3	◺	4 1/2	4 1/2	6	8 1/2	Low damping — tend to PIO. Great deal of trim required
4	⬡	4 1/2	4 1/2	3 3/4	3	Low damping — low static stability. Sluggish — desirable to trim
5	⌂	4	4	2 1/2	3 1/2	Sluggish — tends to wander in attitude
6	◇	5	5	3 3/4	3 1/4	Goosy — lightly damped. No attitude stability — takes nose down trim at touchdown

Figure C-7. Variation of Short Period Roots $(L/D)_{max} = 7$

APPENDIX D

HEADING CONTROL

The military handling qualities specification, 8785B, attempts to insure adequate heading control by limiting the amount of sideslip in aileron-alone turns. The pertinent specification paragraphs are:

3.3.2.4 Sideslip excursions

3.3.2.4.1 Additional sideslip requirements for small inputs

The concept of using sideslip limitations to insure good heading control seems questionable. Certainly there is a strong connection between sideslip and heading control. If the sideslip due to an aileron input is kept small, i.e., there is little excitation of the dutch roll mode, then the heading control will generally be good. However, with such an indirect criterion it seems that:

- Requirements based on a relatively few data points are unlikely to be universally valid.
- Requirements based on data from aircraft with only the conventional lateral/directional modes are unlikely to apply to fully augmented aircraft which have several FCS-introduced modes.

Therefore it was decided to check the 8785B criterion against some more recent data. If our suspicions were confirmed, we would then attempt to derive a substitute criterion.

The first data source examined was Ref. D-1. That report describes a flight (variable stability helicopter) investigation of lateral/directional handling qualities of V/STOL aircraft in final approach (approach speed was 50 kt). While a great many configurations were tested, most of them had very poor pilot ratings and are of little use here. Figure D-1 shows a correlation of pilot ratings with the 8785B sideslip criterion for some of the better configurations*. Note

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*For a precise correlation with the 8785B sideslip requirement, one must determine the value of $\Delta\beta_{max}$ and the φ_t for each level. For the conditions of Fig. D-1, these are $\varphi_{1.8}$ for Level 1 and $\varphi_{2.5}$ for Level 2. Furthermore, a separate figure would be required for each level. The simplified approximation for Level 2 in Fig. D-1 is obtained by assuming the ratio $\varphi_{2.5}/\varphi_{1.8}$ for all the configurations is approximately constant. A value of 1.45 was used.

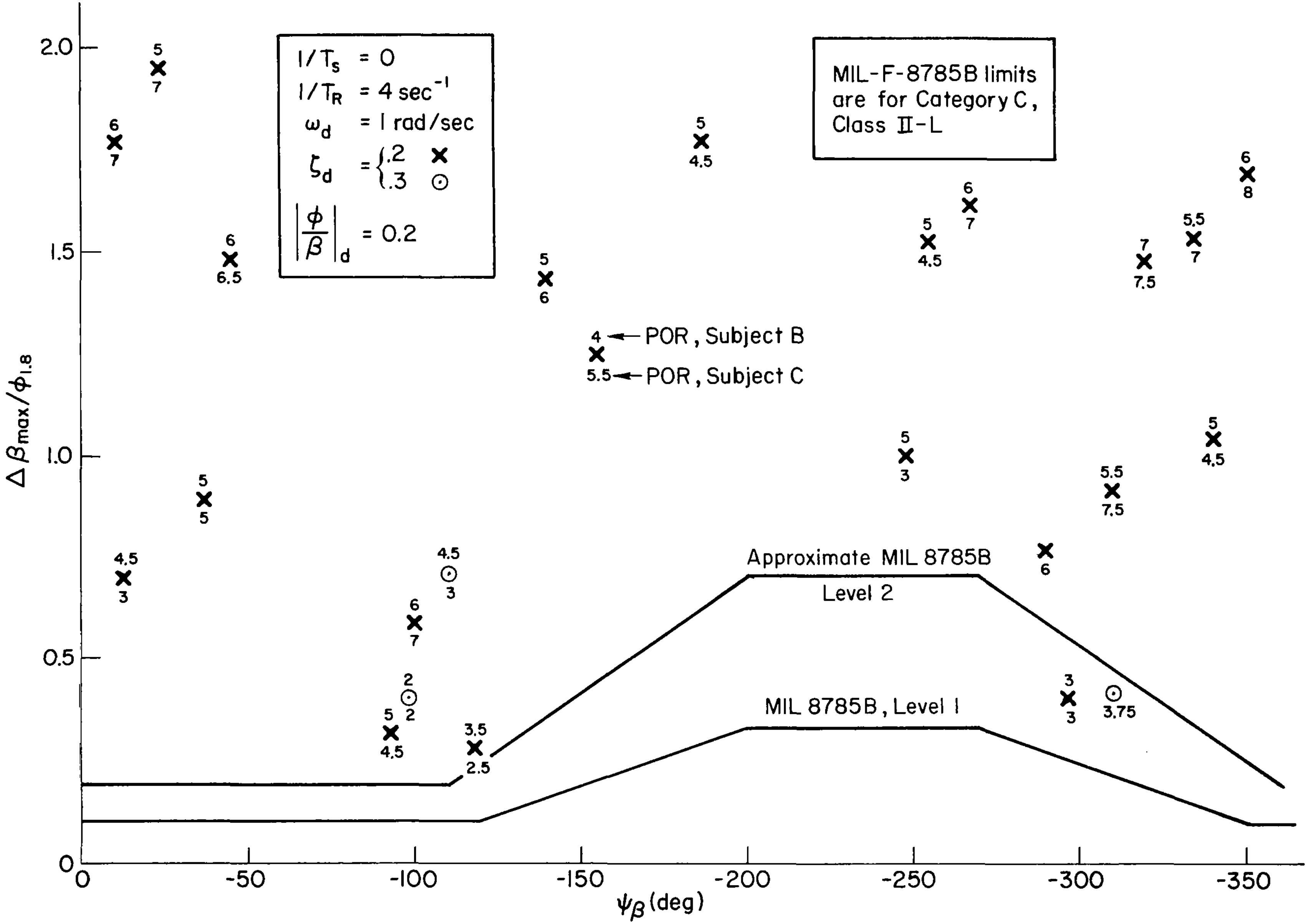


Figure D-1. Pilot Rating Correlation with $\Delta\beta_{max}$

that several configurations exceeded even the Level 2 limits and were still given good ratings. This supports our contention that the 8785B sideslip requirement is a poor one because sideslip per se is of little, or no, concern to the pilot; this criterion is only a circuitous approach to requiring good heading control.

Two of the best rated configurations of Fig. D-1 have interesting dynamic characteristics. The points, (−118, 0.28) and (−97, 0.41), are cases where the bank angle (φ/δ_a numerator) zeros are very nearly equal to the dutch roll poles. In these cases the sideslip response to an aileron input is primarily in the spiral and roll subsidence modes and very little due to the dutch roll mode. In fact, the sideslip is nearly proportional to the bank angle,* with ratios for the two test cases of

$$\beta/\varphi \doteq \begin{cases} 0.13 \text{ for } \zeta_d = 0.2 \\ 0.20 \text{ for } \zeta_d = 0.3 \end{cases}$$

The pilots did not object to the large sideslips because the dutch roll mode was not excited and the heading response was fine. For these two cases the heading response was

---

*For φ/δ_a numerator zeros identical to the dutch roll poles (i.e., $\zeta_\varphi = \zeta_d$, $\omega_\varphi = \omega_d$) and $Y_{\delta_a} = \gamma = W_o = 0$, the lateral dynamics can be defined in terms of $1/T_S$, $1/T_R$, ζ_d, ω_d, and any two stability derivatives. Selecting Y_v and L'_β gives

$$\frac{\varphi}{\delta_a} = \frac{L'_{\delta_a}}{(s + 1/T_S)(s + 1/T_R)}$$

$$\frac{\beta}{\varphi} = -\frac{N'_{\delta_a}}{L'_{\delta_a}} = \frac{g}{U_o}\,\frac{2\zeta_d\omega_d + Y_v}{\omega_d^2}$$

$$\frac{r}{\varphi} = \frac{g}{U_o}\left[\frac{\omega_d^2 + 2\zeta_d\omega_d Y_v + Y_v^2}{\omega_d^2} - \frac{(2\zeta_d\omega_d + Y_v)s}{\omega_d^2}\right]$$

Changing L'_β doesn't change the above responses but does change $|\varphi/\beta|_d$ and the required values of the other derivatives (L'_p, L'_r, N'_β, N'_p, and N'_r).

$$\frac{\psi}{\varphi} \doteq \frac{g}{U_o} \frac{1 - T_\psi s}{s}$$

where $$T_\psi = \begin{cases} 0.34 \text{ sec for } \zeta_d = 0.2 \\ 0.55 \text{ sec for } \zeta_d = 0.3 \end{cases}$$

Clearly the $\Delta\beta_{max}$ parameter of 8785B is not always a measure of dutch roll excitation and heading oscillations. The sideslip response may have little dutch roll component and may be primarily from the roll and spiral modes. Furthermore, when there is very little dutch roll component in the sideslip response the phase angle, ψ_β, of 8785B has little meaning.

More recent flight data are reported in Ref. D-2. This test used the variable stability T-33 to investigate lateral/directional handling qualities during landing approach. A large number of configurations were evaluated and compared with the 8785B requirements. Eight configurations were rated 3 or better and failed to meet the 8785B Level 1 requirement on $\Delta\beta_{max}$. These data and that shown in Fig. D-1 indicate that the 8785B $\Delta\beta_{max}$ criterion is at best overly conservative.

A sizable portion of this project was devoted to trying to find a substitute criterion for $\Delta\beta_{max}$. The objective was to find a criterion which was more directly related to heading control per se. The first parameter tested was τ_ψ, the lag between roll and heading responses to aileron inputs. This parameter was proposed in Ref. D-3 as a potential requirement for good heading control. Flight test measurement of τ_ψ would be a problem because it is defined as the heading lag for a step bank angle change, see Fig. D-2. However, it was considered because it seemed to correlate with the Ref. D-3 opinion data and the definition could probably be modified for flight test.

Figure D-3 shows some pilot rating data of Ref. D-1 plotted versus τ_ψ. The figure shows little correlation between pilot rating and τ_ψ, and drastic differences between the Refs. D-1 and D-3 results. This parameter is apparently too much of a simplification of heading control problems to be a handling qualities criterion, at least by itself.

Next, it was decided to try some measure of dutch roll contamination of the heading or yaw rate response for aileron inputs. The basic idea

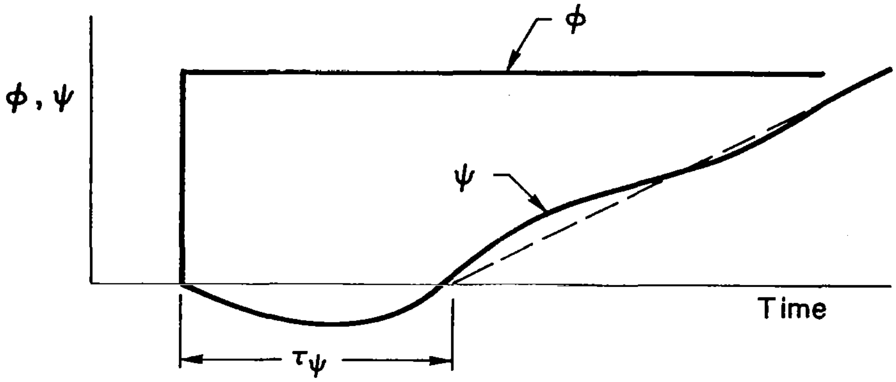


Figure D-2. τ_ψ Example

was that heading control should be good if the dutch roll were not excited, so the degree of dutch roll excitation might be a reasonable handling quality criterion. As an analytically simple first cut, we considered the magnitude, $|r|_d$, and phase, ψ_r, of the dutch roll component of yaw rate for an impulse aileron input. It is assumed that the dutch roll component is written as:

$$|r|_d \, e^{-\zeta_d \omega_d t} \cos \left(\omega_d \sqrt{1 - \zeta_d^2} \;\; t + \psi_r\right)$$

The correlation of pilot rating data from Ref. D-1 with these parameters is shown in Fig. D-4.

Careful comparison of Figs. D-1 and D-4 shows a better correlation with yaw rate than sideslip. The good and bad rating points are more clearly separated in Fig. D-4. This is an encouraging indication of the greater significance of yaw rate (or heading) over sideslip. However, the parameters of Fig. D-4 are not directly suitable for a handling qualities specification. First, they would be difficult to measure in a flight test program. Second, additional data from Ref. D-1 suggest there is an effect of dutch roll damping at constant $|r|_d$ and ψ_r.

The next possibility considered was a variation of the $\varphi_{osc}/\varphi_{av}$ requirement of 8785B (Paragraph 3.3.2.3). Since $\varphi_{osc}/\varphi_{av}$ seems to be a reasonable measure of the dutch roll contribution to φ and resulting

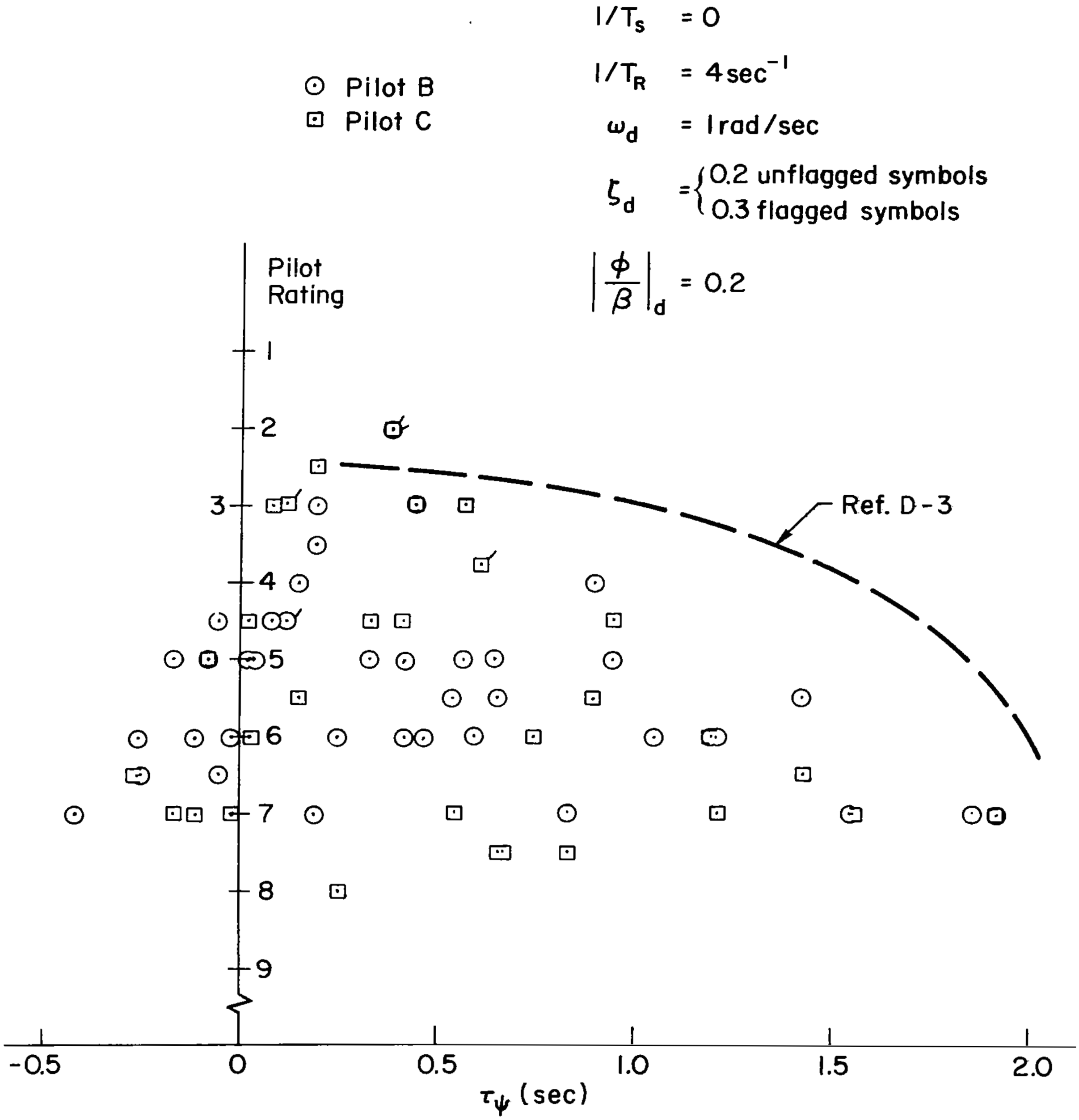


Figure D-3. Pilot Ratings (Ref. D-1) Versus Heading Lag

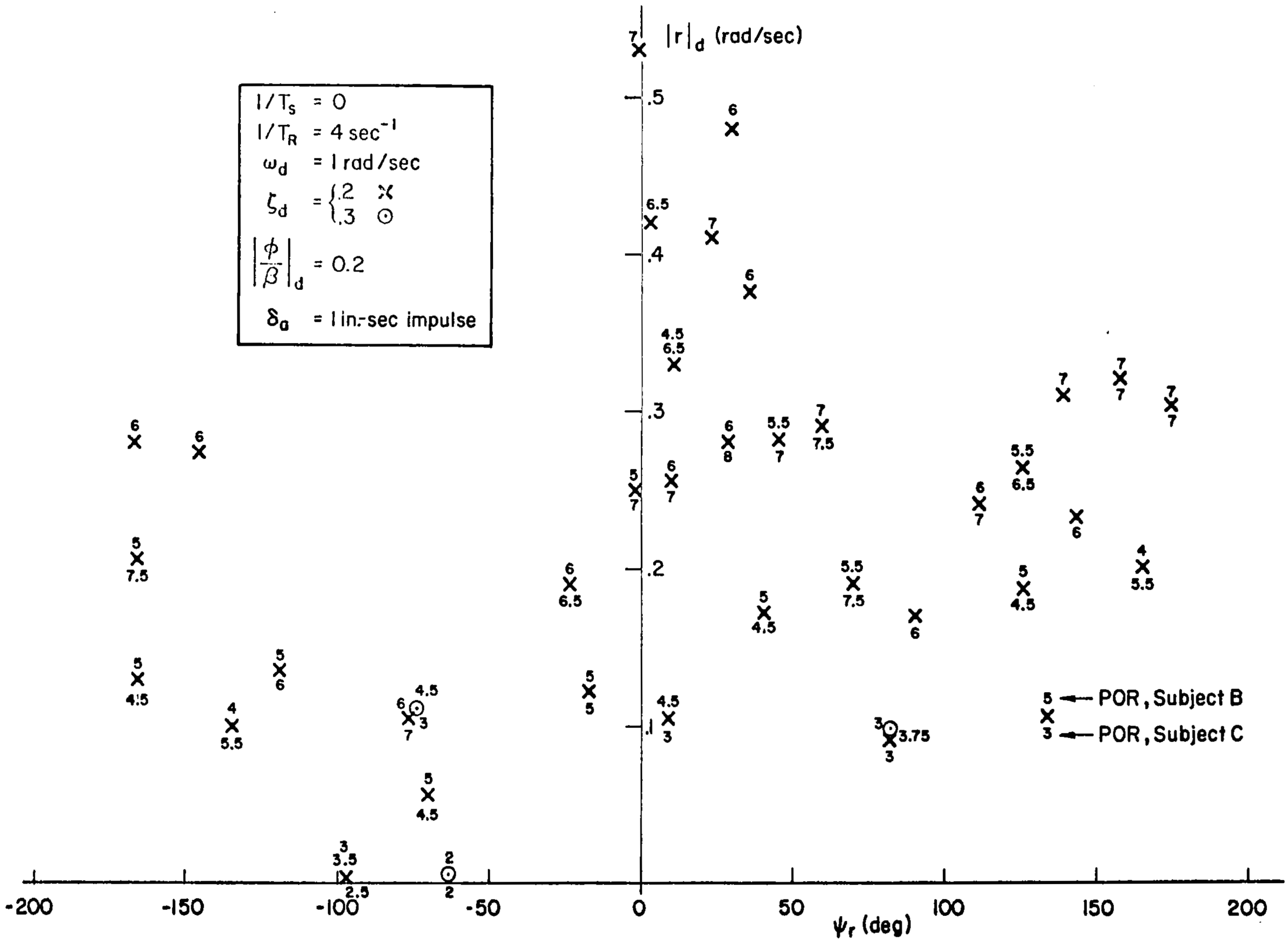


Figure D-4. Pilot Rating Correlation with $|r|_d$

roll control problems r_{osc}/r_{av} might perform the same function for heading control. We used basically the 8785B definition of $\varphi_{osc}/\varphi_{av}$, only changing φ to r. The definition used in the correlation was

$$\zeta_d \leq 0.2 \; : \; \frac{r_{osc}}{r_{av}} = \frac{r_1 + r_3 - 2r_2}{r_1 + r_3 + 2r_2}$$

$$\zeta_d > 0.2 \; : \; \frac{r_{osc}}{r_{av}} = \frac{r_1 - r_2}{r_1 + r_2}$$

where r_1, r_2, and r_3 are the first 3 yaw rate peaks which occur 1 sec or more after the impulse input.

The resulting correlation of Ref. D-1 data is shown in Fig. D-5. The correlation is very similar to that obtained with the $|r|_d$ parameter and is better than that obtained with the 8785B parameter, $\Delta\beta_{max}$. While this initial correlation was fairly good, there was some doubt as to its generality. It seemed unlikely that this parameter could adequately include the effects of variations in dutch roll damping and frequency or could cover aircraft with yaw dampers. Most yaw dampers use wased-out yaw rate/rudder feedback and the additional mode would probably complicate the correlation.

In several earlier investigations conducted by STI, the best metric for heading control had been the heading crossover frequency, ω_{c_ψ}, obtained from pilot/vehicle analysis. The main deterrents to using this metric in the current program were the complexity of the ω_{c_ψ} calculation and the difficulty of flight test verification. These features detract from the desirability of ω_{c_ψ} as a handling qualities specification; however, it can be computed from measured roll and heading/aileron frequency response data.

The pilot/vehicle analysis of heading control uses the feedback structure shown in Fig. D-6. The pilot roll loop describing function is usually assumed to be of the form

$$Y_{p_\varphi} = K_\varphi(T_L s + 1)e^{-\tau s}$$

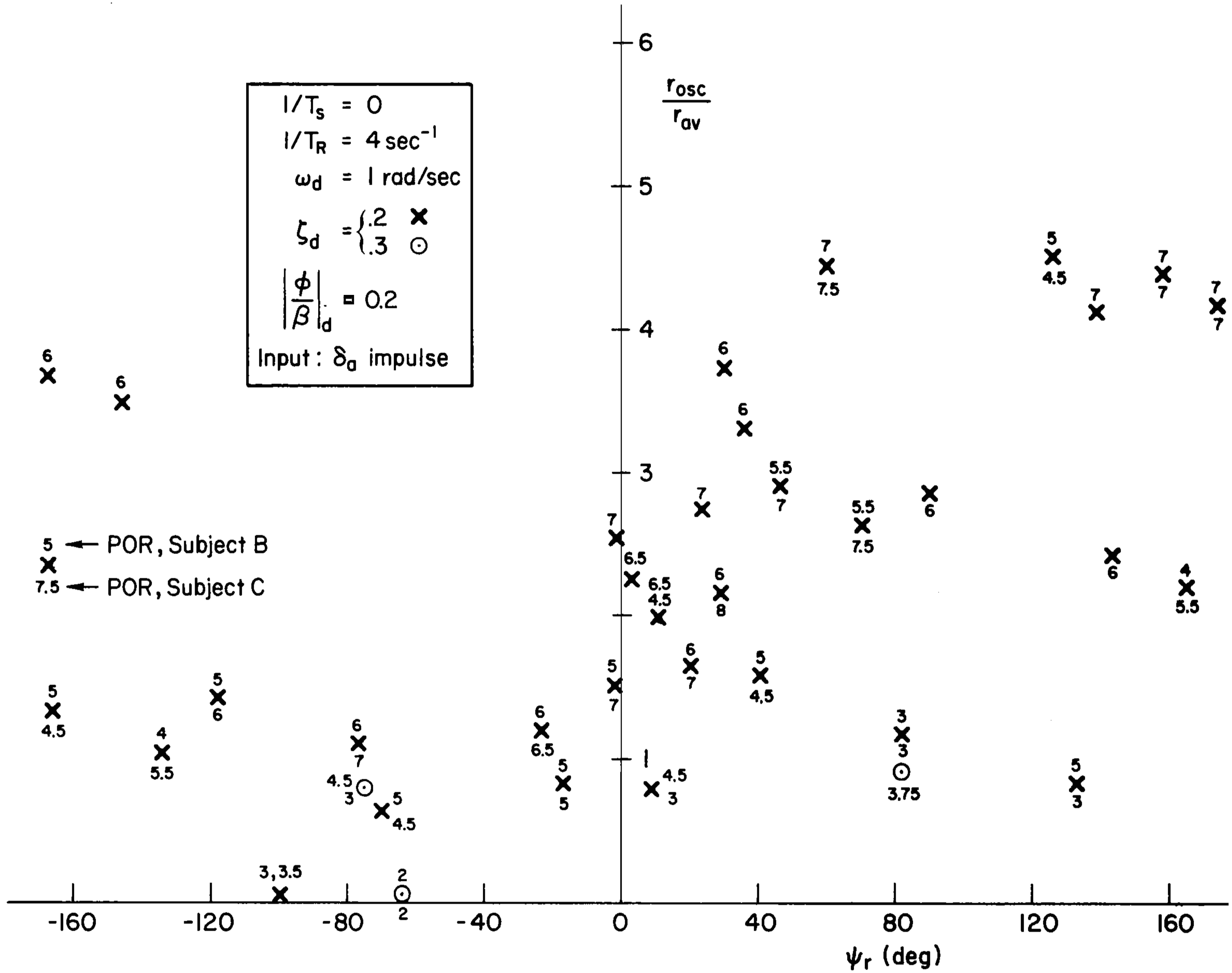


Figure D-5. Pilot Rating Correlation with r_{osc}/r_{av}

where the lead is approximately equal to the roll mode time constant and the time delay, τ, is roughly 0.4 sec. The outer loop describing function, Y_{p_ψ}, is assumed to be a pure gain.

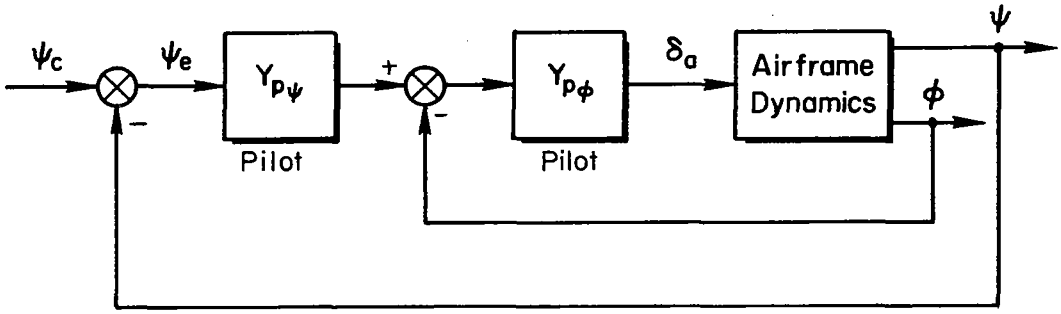


Figure D-6. Loop Structure for Manual Control of Heading

An early correlation with rating data from Ref. D-1 is given in Fig. D-7. These results were obtained by closing the roll loop with a gain margin of 6 dB and a phase margin of 45 deg. For those configurations which had a roll crossover frequency of more than 1.5 rad/sec, the heading loop was closed with margins of 6 dB and 45 deg. The poor roll closure cases were dropped to eliminate configurations which might have been rated poorly because of roll control problems.

Figure D-7 has several interesting features. First, there is a general trend of rating with ω_{c_ψ} (solid line), similar to that obtained in earlier studies. In fact, the limit of a crossover frequency of approximately 0.3 rad/sec for a rating of 3.5 or better agrees very well with Refs. D-3 and D-4. However, there are numerous points at low ω_{c_ψ} rated better than the trend and some at high ω_{c_ψ} rated worse. For the low ω_{c_ψ} points the pilot commentary indicated that the pilot could improve his control by using the rudder. Thus, the ratings for these cases should be better than indicated by analysis of aileron-alone control. When the pilot got little benefit from using the rudder, the ratings follow the trend line.

For the high ω_{c_ψ} cases rated relatively poorly, the pilots complained of heading wander. These were cases in which the φ/δ_a zeros were the same as the dutch roll poles, i.e., the aileron did not excite the dutch

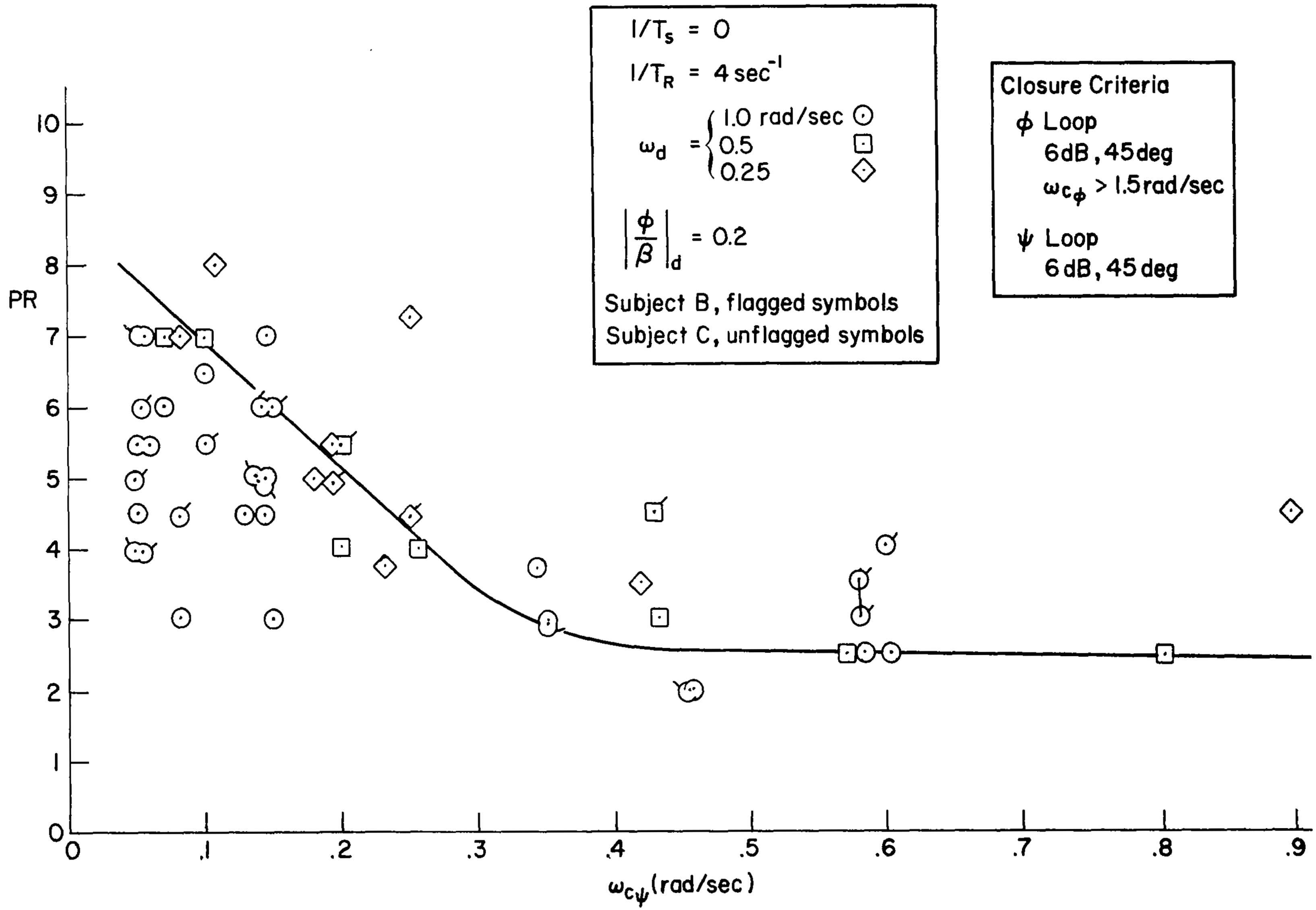


Figure D-7. Pilot Rating Correlation with Heading Crossover Frequency mode. However, the lateral gusts did excite the dutch roll and if the dutch roll damping were too low there was a tendency for a heading oscillation or wander. Since control of this wander could only be with the rudder, the configurations were down-rated slightly.

Thus, ω_{c_ψ} appeared to be a reasonably good metric for heading control, at least aileron alone. It might even be adequate by itself as a criterion for ratings of 3.5 or better. However, work was continued on including the effects of the pilot's using the rudder. As a preliminary study along these lines, five configurations which had $\omega_{c_\psi} = 0.05 - 0.06$ rad/sec and ratings spreading from $4 - 7$ (see Fig. D-7) were examined. The best rated configurations were those for which a pure gain aileron-to-rudder crossfeed would nearly coordinate the turns. If an equalized crossfeed was required, the ratings were poorer. The interpretation of these results is that a pilot can, and will, use a pure gain crossfeed if this will improve his heading control; and his rating may be good if the crossfeed gain is not excessive. If an equalized crossfeed is required, the pilot cannot do it accurately so his heading control and rating will be poor.

Next an analysis of lateral handling quality data obtained by Princeton University with their variable stability Navion was made. Unfortunately, most of the tests were conducted in such a manner that it is impossible to isolate heading control problems. The parameter variations from one configuration to another usually resulted in changing several handling qualities factors simultaneously, e.g., heading control, directional stability, and gust sensitivity. However, two sets of data were found in Ref. D-5 for which the spiral, roll subsidence, and dutch roll modes plus the effective dihedral (L'_β) were held nearly constant.

Within each set the primary factors being varied were then roll control (φ/δ_a numerator) and heading control (ψ/δ_a numerator). For these two data sets the pilot/vehicle analysis procedure discussed above was applied. The resulting heading loop crossover frequency (ω_{c_ψ}) is correlated with the pilot rating in Fig. D-8. The roll control was generally adequate, although the φ/δ_a zeros for one configuration were

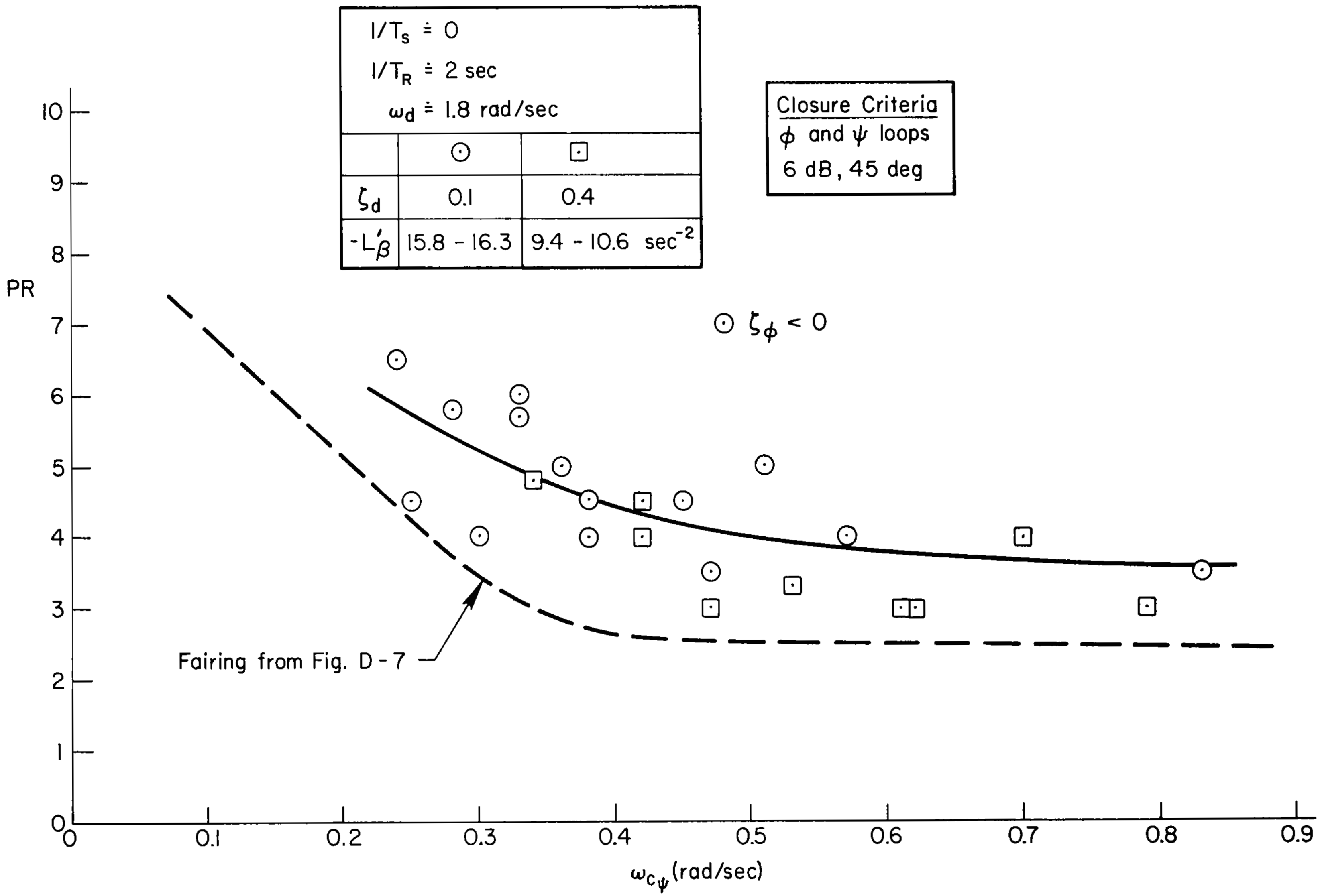


Figure D-8. Pilot Rating Correlation with Heading Crossover Frequency in the right half plane ($\zeta_\varphi < 0$). Except for that point there is generally a fairly good correlation between pilot rating and crossover frequency. However, pilot commentary are not included in Ref. D-5, so we cannot definitely establish that the cause of the rating differences is heading control.

Also shown in Fig. D-8 (dashed line) is the fairing of the Ref. D-1 data given in Fig. D-7. The better ratings from the NAE test (Ref. D-1) are probably due to a much lower effective dihedral ($|\varphi/\beta|$ of 0.2 versus roughly 6.5) which means a lower gust sensitivity. Nevertheless, the data from both sources seemed to confirm the importance of heading control and the general validity of the heading crossover frequency as a handling qualities criterion.

As noted above the analysis of most lateral handling qualities data is difficult because of the effects of several factors are intermixed. We have found that several factors must usually be considered in evaluating lateral handling qualities data. Among the important factors which have been identified are:

- Bank angle control
- Heading control, aileron-alone
- If aileron-alone control is not adequate, ability to coordinate turns with rudder
- Gust disturbances, heading wander and roll

Because of these problems a simulation experiment to isolate heading control problems was designed.

The basic objectives of this experiment were to:

- Verify the importance of manual control of heading with ailerons alone as a handling quality factor.
- Verify the use of heading crossover frequency, ω_{c_ψ}, as a key metric.
- Obtain data on effects of the pilot's ability to use the rudder to improve heading control.

Fourteen configurations were selected and all had nearly identical roll, spiral, and dutch roll modes, as listed below:

$$1/T_R \doteq 1.5 \text{ sec}^{-1}$$

$$1/T_s \doteq 0$$

$$\zeta_d \doteq 0.2$$

$$\omega_d \doteq 1 \text{ rad/sec}$$

Seven of the configurations had a low effective dihedral, $L'_\beta = -1 \text{ sec}^{-2}$, and seven had a high dihedral, $L'_\beta = -6 \text{ sec}^{-2}$. Each group of seven had φ/δ_a zeros located as shown in Fig. D-9. Also shown in Fig. D-9 are the computed heading crossover frequencies for both groups. This set of configurations was selected to have several important features:

- Roll control good to excellent.
- Heading control from poor to excellent.
- Significant change in heading control with the same φ/δ_a transfer function.
- Significant differences in the rudder inputs required to coordinate turns.

No configuration was expected to have poor roll control because the pole-zero separations were all relatively small and the roll mode time constant was low, 2/3 sec. However, some of the low dihedral configurations had very poor heading control (aileron alone), see Fig. D-9.

So that we could isolate the several factors which usually influence pilot ratings in similar tasks, the test was run without any atmospheric turbulence and both with and without the use of rudder. Gust inputs were eliminated so that we had seven pairs of configurations with the same φ/δ_a transfer functions and differing only in heading control. With appreciable lateral gust inputs there could be a significant degradation in pilot rating of the high dihedral configurations because of the large gust sensitivity.

The longitudinal dynamics were held constant with very good characteristics. A high level of speed stability was provided so the pilot could level off without a significant speed change. The lateral dynamics were varied to provide the characteristics given above. Specific values of the stability derivatives are given in Table D-1.

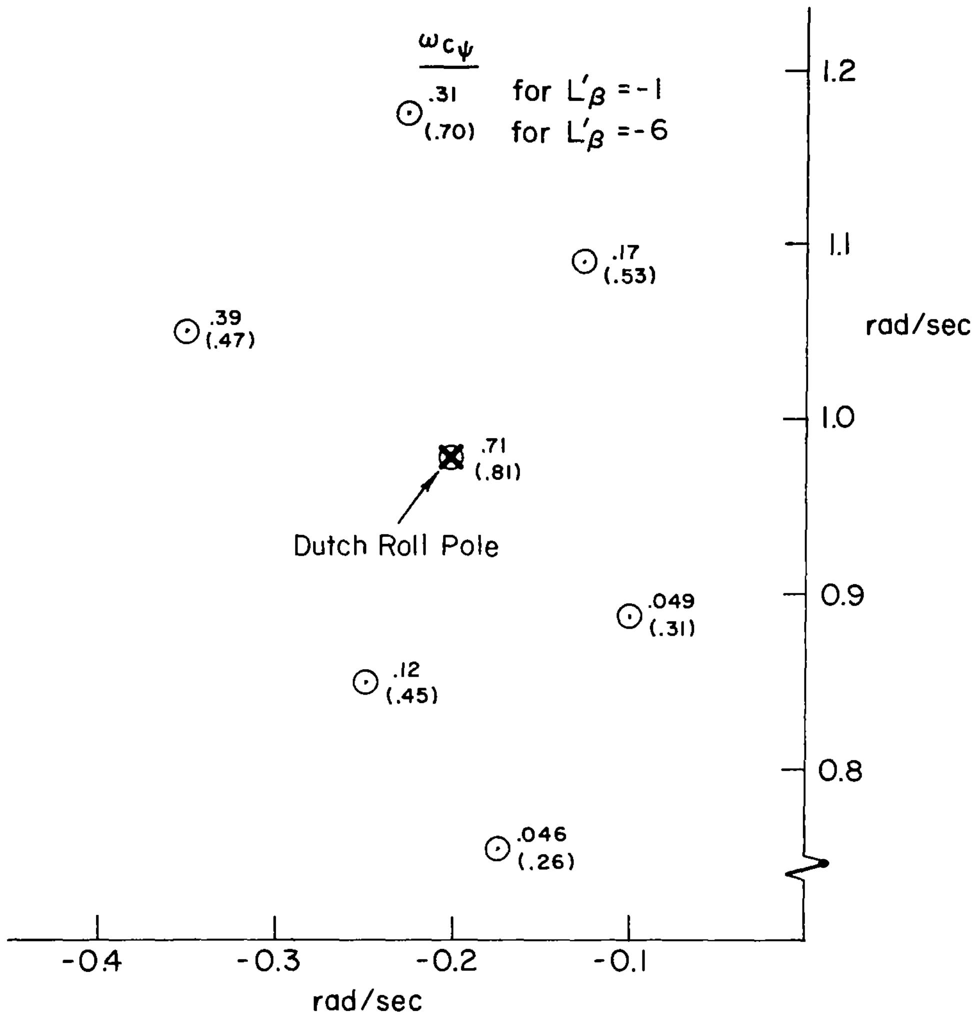


Figure D-9. φ/δ_a Zeros for First Heading Control Experiment

TABLE D-1. AERODYNAMIC CHARACTERISTICS FOR FIRST HEADING CONTROL EXPERIMENT

Configuration	ζ_φ	ω_φ (rad/sec)	Y_v (sec^{-1})	L_β' (sec^{-2})	L_p' (sec^{-1})	L_r' (sec^{-1})	N_β' (sec^{-2})	N_p' (sec^{-1})	N_r' (sec^{-1})	$N_{\delta a}'/L_{\delta a}'$
1	0.13	0.90	-0.2	-1.0	-1.626	0.1110	1.202	0.5763	-0.0731	-0.3782
2	0.11	1.10	↓	↓	↓	↓	↓	↓	↓	0.00126
3	0.22	0.80	↓	↓	-1.496	0.2003	0.9816	0.1302	-0.2082	-0.3579
4	0.20	1.00	↓	↓	↓	↓	↓	↓	↓	-0.0200
5	0.19	1.20	↓	↓	↓	↓	↓	↓	↓	0.3787
6	0.28	0.90	↓	↓	-1.430	0.6474	0.6838	-0.2859	-0.2537	0.06736
7	0.32	1.09	↓	↓	↓	↓	↓	↓	↓	0.3895
8	0.13	0.90	-0.2	-6.0	-1.636	0.4132	1.233	0.1948	-0.0656	-0.07137
9	0.12	1.10	↓	↓	-1.627	0.4120	1.217	0.1890	-0.0650	-0.00250
10	0.22	0.80	-0.3	↓	-1.497	0.6001	1.043	0.1194	-0.1000	-0.06962
11	0.19	1.00	↓	↓	-1.497	0.6000	1.033	0.1192	-0.1000	-0.00999
12	0.18	1.20	↓	↓	-1.492	0.6360	1.029	0.1166	-0.1150	0.06049
13	0.29	0.91	↓	↓	-1.310	1.976	0.8279	0.0537	-0.2509	-0.01117
14	0.32	1.09	↓	↓	-1.280	2.3050	0.8100	0.0442	-0.3070	0.04391

Derivatives are given in stability axes.

Approach conditions

$V = 180$ kt $= 304$ ft/sec

$\gamma = -3$ deg

The test was conducted on the NASA ARC Flight Simulator for Advanced Aircraft (FSAA) to provide the best possible duplication of lateral motion cues. Three ARC test pilots served as subjects. The simulation was started with the aircraft at an altitude of 1,000 ft and on the ILS beam. The aircraft was flown IFR (using conventional ILS needles) down to 650 ft where a transition to VFR was made. The remainder of the approach was flown using the Redifon visual presentation (see Appendix E).

The heading characteristics were evaluated by a series of pilot initiated maneuvers such as S-turns and discrete heading changes. For most configurations the pilots would also level off just above the runway and fly down the runway maneuvering from one side to another. They felt this was a particularly good means of checking their ability to make lateral corrections because they had a very good visual reference.

For most of the runs the pilot location relative to the airplane c.g. was simulated at typical SSV values, 70 ft forward and 6 ft above the c.g.* However this resulted in a rough ride for some configurations, notably 1, 3, 5, and 7. For those configurations the aileron yaw was very large ($0.35 < |N'_{\delta_a}/L'_{\delta_a}| < 0.39$) and rapid aileron inputs produced large side accelerations at the cockpit. To check on this effect some runs were also made with the simulated pilot location at the c.g. To further alleviate the problem, the aileron effectiveness was reduced to a value near the minimum for satisfactory pilot rating. In most cases the maximum roll acceleration, $L'_{\delta_a}(\delta_a)_{max}$, was 15 deg/sec^2, but several runs were made at 25 deg/sec^2. The rating data is summarized in Table D-2.

The correlation of pilot ratings with ω_{c_ψ} is shown in Fig. D-10. The data shown there are for the nominal pilot location and for Configurations 1-7 for the lower roll power. There are several interesting facets of the data shown in Fig. D-10 and these are discussed below. First, the general trend of pilot rating versus ω_{c_ψ} is similar to that shown earlier. However, we note that Configurations 5, 7, 8, and 10 have similar values of ω_{c_ψ} but 5 and 7 are rated considerably poorer than 8 and 10. One

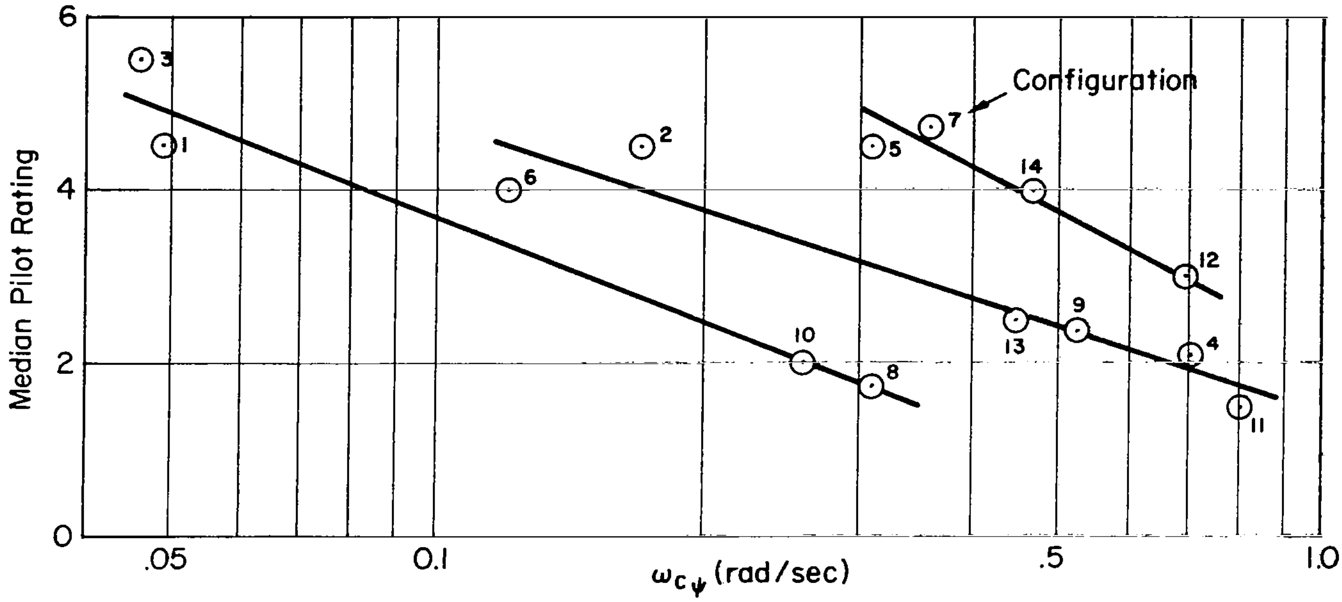
*These distances are measured in stability axes, i.e., parallel and perpendicular to the steady-state velocity vector. Location effects due to trim angle of attack were not simulated.

TABLE D-2

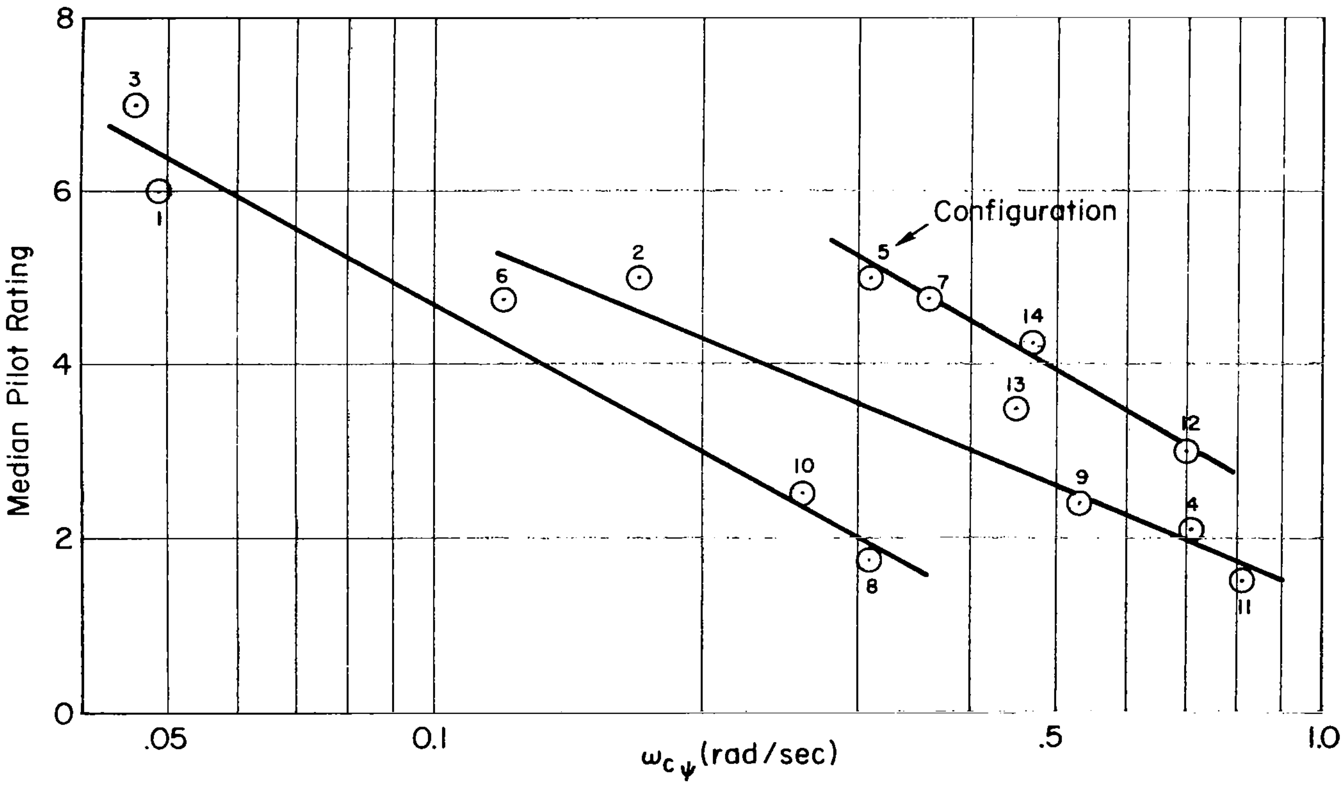
PILOT RATING DATA FROM FIRST HEADING CONTROL EXPERIMENT

CONFIG.	PILOT LOCATION	SUBJECT	$L_{\delta_a}\delta_{a_{max}}$ (DEG/SEC^2)	PILOT RATINGS*
1	NOM	A	15	4-5 , 7
		A	15	4-5 , 7
		B	25	6 , 7
		B	15	5 , 5
		C	15	6 , 6
		C	15	4.25 , 4.25
	c.g	C	15	7 , 7
		C	15	6.5 , 6.5
2	NOM	A	15	3 , 4
		A	15	4 , 4
		B	15	5 , 5
		C	15	4.5 , 5.5
		C	15	5 , 5
		C	25	5.5 , 5.5
3	NOM	A	15	5 , 7
		A	15	6 , 8
		B	15	5 , 7
		B	15	6-6.5 , 7.5
		C	15	4 , 5
		C	15	6 , 6
		C	25	6.5 , 7
	c.g.	A	15	7 , 8-9
4	NOM	A	25	1 , 1
		A	15	1 , 1
		A	25	1 , 1
		B	25	2.5 , 2.5
		B	15	2 , 2
		C	25	2.25 , 2.25
		C	25	2.5 , 2.5
		C	15	2.25 , 2.25
5	NOM	A	15	4 , 4
		A	15	4 , 5
		B	25	5.5 , 5.5
		B	15	4 , 4
		B	15	5 , 5
		C	15	7 , 7
		C	25	6.5 , 6.5
		C	15	6.5 , 6.5
		C	25	6.5 , 7
	c.g	A	15	4 , 4
		A	15	6 , 7
		B	25	6 , 6
6	NOM	A	15	4-5 , 6-7
		A	15	4 , 6
		B	15	4 , 5
		B	15	4 , 4.5
		C	15	2 , 2
		C	15	2.5 , 3
	c.g.	C	15	2.5 , 3
		C	25	2.5 , 3.5
7	NOM	A	15	5 , 7
		A	15	5 , 5
		B	15	4.5-5 , 4.5-5
		C	15	3.75 , 3.75
		C	15	4.5 , 4.75
	c.g.	C	15	4.75 , 4.75
8	NOM	A	15	1 , 1
		A	15	3 , 4
		C	25	1.5 , 1.5
		C	25	2 , 2
9	NOM	A	15	1 , 1
		A	15	2 , 2
		C	25	2.75 , 2.75
		C	25	3.5 , 3.5
10	NOM	A	15	4 , 4
		A	25	2 , 3
		A	15	1-2 , 1-2
		B	25	2 , 2
	c.g.	A	15	2-3 , 3-4
11	NOM	A	15	1 , 1
		B	25	2 , 2
12	NOM	A	25	2 , 2
		A	15	1-2 , 1-2
		B	25	3 , 3
		C	15	4 , 4
		C	25	3.5 , 3.5
13	NOM	A	15	1 , 1
		A	15	2 , 2
		B	25	2.5 , 3.5
		B	25	2.5 , 3.5
		C	25	4 , 4.5
		C	25	4 , 4
14	NOM	A	15	1 , 1
		A	15	4 , 5
		C	25	4 , 4.5
		C	25	4 , 4

*First rating is with rudder; second is aileron alone.



a) Ratings With Rudder



b) Ratings for Aileron Alone

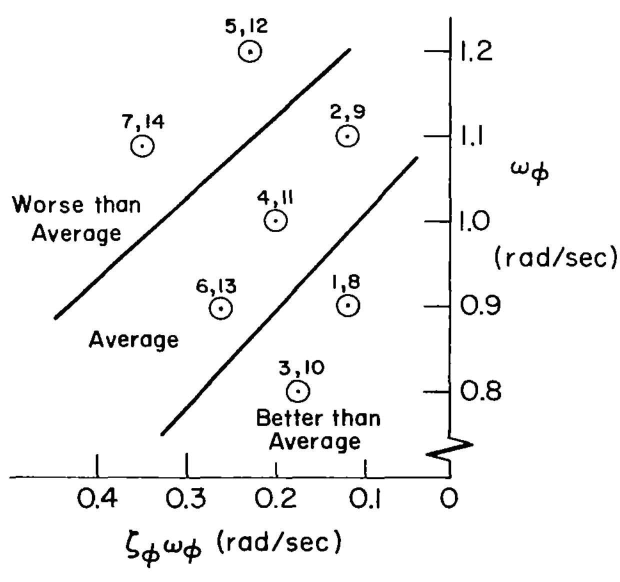
Figure D-10. Rating Correlation with ω_{c_ψ} for First Heading Control Experiment explanation is the differences in roll control characteristics. If this explanation is the correct one, Configurations 12 and 14 should be rated somewhat worse than indicated by ω_{c_ψ} because they have the same roll characteristics as 5 and 7. Likewise, 1 and 3 should be rated somewhat better. Figure D-10 does show 12 and 14 rated slightly worse than the general trend but we can't tell about 1 and 3 because there are no other data points at the low ω_{c_ψ}.

If we assume that this argument is correct, the data correlate very well with ω_{c_ψ} when subdivided into three groups:

1, 3, 8, 10	Better than average pilot rating
2, 4, 6, 9, 11, 13	Average pilot rating
5, 7, 12, 14	Worse than average pilot rating

This separation in terms of the roll zeros is shown in the following sketch. From this sketch the groupings of configurations are difficult to understand. On the basis of roll control bandwidth and the effect of the roll loop on dutch roll damping, we cannot explain why:

- 2 is rated better than 5 or 7
- 6 is rated worse than 1 or 3



On the other hand, the groupings are well correlated with aileron yaw as follows:

$-0.38 \leq N'_{\delta_a}/L'_{\delta_a} \leq -0.07$	Better than average
$-0.02 \leq N'_{\delta_a}/L'_{\delta_a} \leq 0.001$	Average
$0.04 \leq N'_{\delta_a}/L'_{\delta_a} \leq 0.39$	Worse than average

This separation works except for Configuration 6 which has $N'_{\delta_a}/L'_{\delta_a} = 0.07$ and is in the average group. However this configuration has highly adverse N'_p which offsets the proverse aileron yaw. The above suggests that pilots have a distinctive preference for adverse yaw and a bias against proverse yaw. Further exploration of this hypothesis was one reason for conducting a second heading control experiment which will be described below; but first we will discuss some of the other results from the first test.

The effect of using the rudder can be seen by comparing Fig. D-10a and D-10b, but a more direct measure is the average difference in pilot rating with rudder and aileron alone. The average differences (for nominal pilot location) are:

Configuration	$\overline{\Delta PR}$	Configuration	$\overline{\Delta PR}$
1	1.00	8	0.25
2	0.33	9	0
3	1.25	10	0.25
4	0	11	0
5	0.19	12	0
6	1.00	13	0.42
7	0.45	14	0.35

Use of the rudder has the greatest effect for the low dihedral, $\omega_\varphi/\omega_d < 1$, adverse yaw, cases (1, 3, and 6). For these configurations heading control without the rudder is poor and rudder-into-the-turn should help considerably. It was somewhat surprising that the rudder effect for 3 was not larger relative to the effect for 1 and 6. With

Configuration 3 a pure gain aileron-to-rudder crossfeed would coordinate the turns, while 1 requires a lead/lag crossfeed for coordination and 6 requires a lag crossfeed. Perhaps Configuration 3's ratings with rudder would have improved with more familiarization.

The proverse yaw configurations (2, 5, and 7) show considerably less effect of the rudder. This mainly reflects the pilots' reluctance (also noted in other experiments) to use opposite rudder in a turn. The general reduction in the effect of rudder for the high dihedral cases (8-14) is because the aileron-alone heading control is so much better that there is little need to use the rudder.

As noted earlier, some runs were also made with the simulated pilot location at the vehicle c.g. This was done because of adverse pilot comments on the large lateral accelerations induced by rapid aileron inputs, especially for Configurations 1, 3, 5, and 7. To check this effect nine runs were made with low dihedral configurations with the pilot at the c.g. While this shift was expected to improve the pilot ratings, the data show a consistent trend to worse ratings, by roughly one rating point, for the pilot at the c.g. The pilots complained of a "woozy feeling" and thought the dutch roll damping had been decreased. Since the only difference is in the lateral acceleration cues, the dutch roll modal responses were checked.

In the dutch roll mode, the lateral acceleration at the c.g. is 5-6 times as great as that at the forward location. The magnitude of a_y/ψ is about 0.035 g's/deg at the c.g. and 0.0059 – 0.0067 at the cockpit. For those configurations (1-7) the dutch roll is fairly flat (i.e., little roll-coupling) and is nearly an oscillation about the cockpit. The higher lateral accelerations explain the pilots' adverse reactions to being at the c.g. Although they did not experience the large initial accelerations due to aileron inputs, the accelerations, once the dutch roll mode was excited, were quite large.

While the results of this experiment indicated that ω_{c_ψ} has some value as a heading control metric the results were not conclusive. There is the problem of apparently different criterion for proverse and adverse yaw configurations. There is also the question of how well ω_{c_ψ} works for different values of dutch roll frequency or damping. For these reasons it was decided to conduct a second heading control simulation.

The primary objective of the experiment was to investigate the relationship between roll control and heading control for several values of dutch roll frequency and damping. To accomplish these objectives, ten groups of four test configurations were selected.* Within each group, the aileron/roll characteristics were held constant (constant roll numerator zeros) while the heading responses were varied. The selected variations provided heading control characteristics ranging from very good to poor.

In all cases the spiral mode was neutrally stable and the roll subsidence mode ($1/T_R$) was at 1.5. The relationship between the dutch roll pole and the complex roll numerator zeros for each group is shown graphically in Fig. D-11. Four values of dihedral (L'_β) were selected for each group to provide variations in the heading characteristics. The remaining lateral derivatives were calculated to give the desired roll characteristics for that group. Great care was taken to insure that the derivatives obtained were realistic for shuttle-type configurations. For a given roll-aileron characteristic, the amount of roll-yaw coupling (N'_{δ_a}, N'_p) turns out to be roughly inversely proportional to L'_β so that the high dihedral cases had much better heading characteristics than the low dihedral cases. The values of L'_β used varied from −0.5 to −10. The complete list of stability derivatives is given in Table D-3.

The pilot location was taken as 70 ft in front of and 6 ft above the center of gravity to simulate a typical shuttle configuration. These are the same values used in the first test but for additional realism a 10 deg angle of attack was also simulated. Thus, the pilot location relative to stability axes was 68 ft forward and 18 ft above the c.g.

The longitudinal dynamics were optimized to allow the pilots to focus their full attention on the lateral task. In addition, the drag characteristics were manipulated to make the aircraft speed stable at 180 kt.

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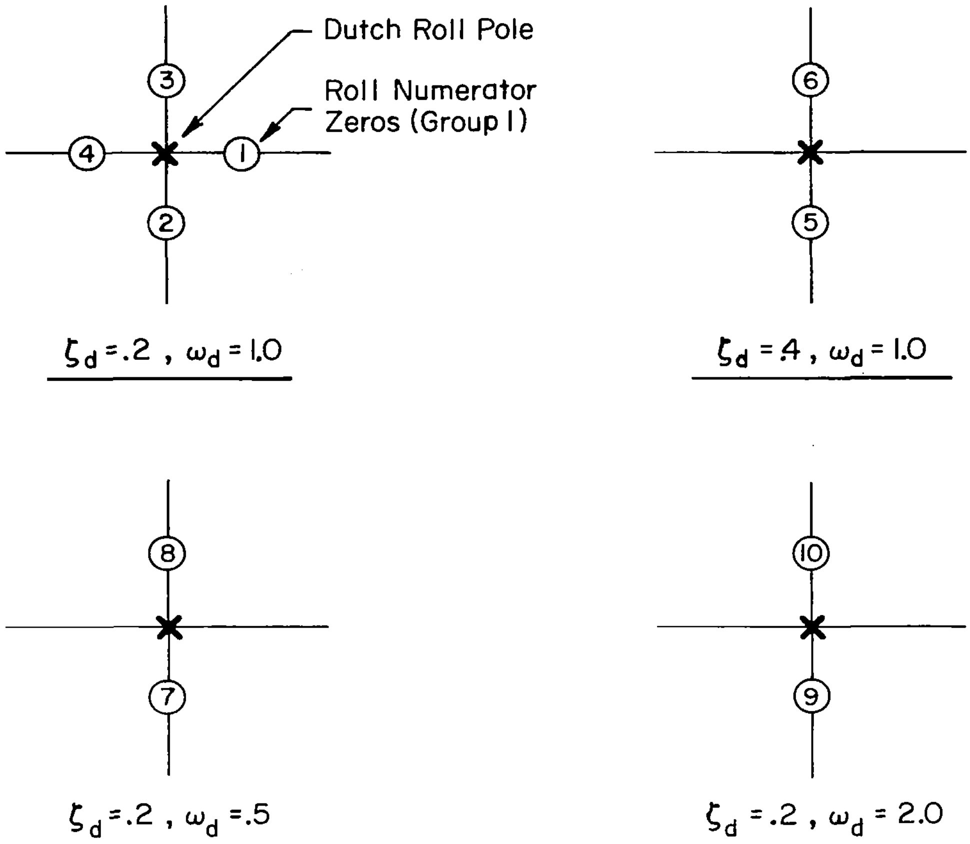
*There were only 3 configurations in Groups 9 and 10.



Group	ω_φ/ω_d	ζ_φ	Dominant Roll-Yaw Coupling
1	1.0	0.1	Adverse then Proverse
2	.8	0.2	Adverse
3	1.2	0.2	Proverse
4	1.0	0.3	Proverse then Adverse
5	.8	0.4	Adverse
6	1.2	0.4	Proverse
7	.8	0.2	Adverse
8	1.2	0.2	Proverse
9	.9	0.2	Adverse
10	1.1	0.2	Proverse

Figure D-11. Summary of Dutch Roll Pole — Roll Numerator Zero Relationships for Test Configurations

TABLE D-3

STABILITY DERIVATIVES FOR SECOND HEADING CONTROL EXPERIMENT

CONFIGU-RATION	Y_v (SEC^{-1})	L'_β (SEC^{-2})	L'_p (SEC^{-1})	L'_r (SEC^{-1})	N'_β (SEC^{-2})	N'_p (SEC^{-1})	N'_r (SEC^{-1})	$N'_{\delta_a}/L'_{\delta_a}$
1A	-0.2	-1	-1.674	-0.01390	1.214	0.6406	-0.02702	-0.2071
1B	-0.2	-3	-1.677	0.04961	1.235	0.2990	-0.01922	-0.07744
1C	-0.2	-6	-1.669	0.09035	1.225	0.1990	-0.01979	-0.03658
1D	-0.2	-10	-1.668	0.1360	1.227	0.1630	-0.01458	-0.02266
2A	-0.2	-1	-1.525	0.1878	1.036	0.2285	-0.1772	-0.4041
2B	-0.2	-3	-1.528	0.3786	1.062	0.1556	-0.1764	-0.1474
2C	-0.2	-6	-1.524	0.9116	1.119	0.1440	-0.1822	-0.08316
2D	-0.2	-10	-1.509	1.570	1.189	0.1362	-0.1955	-0.05691
3A	-0.2	-1	-1.482	0.2339	0.9518	0.07351	-0.2190	0.4018
3B	-0.2	-3	-1.471	0.8121	1.026	0.1311	-0.2100	0.1151
3C	-0.2	-6	-1.472	1.306	1.097	0.1316	-0.2275	0.04712
3D	-0.2	-10	-1.433	2.254	1.157	0.1250	-0.2494	0.02223
4A	-0.2	-0.5	-1.359	0.06938	0.7579	-0.6581	-0.3577	0.2995
4B	-0.2	-1	-1.395	0.3939	0.7238	-0.2760	-0.3167	0.1845
4C	-0.2	-3	-1.362	1.296	0.8107	0.00843	-0.3452	0.03661
4D	-0.2	-6	-1.314	2.602	0.9387	0.07289	-0.4044	-0.00442
5A	-0.3	-1	-1.526	0.3718	0.9853	0.2784	-0.4874	-0.4345
5B	-0.4	-3	-1.544	0.8573	1.063	0.1952	-0.3769	-0.1709
5C	-0.4	-6	-1.535	1.682	1.172	0.1679	-0.3905	-0.1031
5D	-0.4	-10	-1.507	2.886	1.305	0.1542	-0.4147	-0.07493
6A	-0.2	-1	-1.480	0.5634	0.9751	0.2044	-0.6259	0.2849
6B	-0.2	-3	-1.389	1.956	1.168	0.1943	-0.6993	0.03771
6C	-0.2	-6	-1.294	3.718	1.327	0.1602	-0.7986	-0.00641
6D	-0.2	-10	-1.188	5.852	1.529	0.1427	-0.8995	-0.02421
7A	-0.2	-0.5	-1.517	0.00712	0.2809	0.1972	0.03309	-0.2218
7B	-0.2	-1	-1.526	-0.1033	0.2784	0.1485	0.04375	-0.1103
7C	-0.2	-3	-1.519	-0.3577	0.2415	0.1051	0.03573	-0.02443
7D	-0.2	-6	-1.531	-0.7117	0.2258	0.1019	0.02679	-0.00992
8A	-0.2	-0.5	-1.479	0.1626	0.2279	0.03976	-0.02194	0.2398
8B	-0.2	-1	-1.484	0.1989	0.2401	0.09367	-0.02563	0.1098
8C	-0.2	-3	-1.456	0.5923	0.2483	0.1014	-0.03910	0.03353
8D	-0.2	-6	-1.437	1.171	0.2890	0.1117	-0.05472	0.01001
9A	-0.2	-3	-1.512	0.3540	3.956	0.1420	-0.6055	-0.2603
9B	-0.2	-6	-1.491	0.8081	3.971	0.1113	-0.6233	-0.1362
9C	-0.2	-10	-1.488	1.323	4.024	0.1124	-0.6309	-0.08727
10A	-0.2	-3	-1.501	0.4681	3.928	0.1331	-0.5938	0.2383
10B	-0.2	-6	-1.496	1.013	4.012	0.1417	-0.5847	0.1114
10C	-0.2	-10	-1.486	1.641	4.076	0.1312	-0.5993	0.06173

Note: Derivatives are given for stability axes.

This allowed the pilots to fly down to the runway and then to maneuver laterally at low altitudes (25-50 ft) without touching down.

The test procedure was the same as in the first heading control experiment. Each run was initiated at 1,000 ft of altitude on a 3° glide path. The cloud height was set to approximately 650 ft giving the pilot about 30 sec in the clouds and 90 sec of visual flight using the Redifon display system. The piloting task was to maneuver the aircraft about the localizer and runway centerline. Each pilot was asked to rate heading control. The maneuvers used to make these evaluations were as follows:

- Put in and take out lateral offsets from the localizer (IFR) and runway centerline (VFR)
- Turns to headings (IFR)
- S turns down the runway at low altitude

Because of the extreme forward pilot location, some configurations (especially the proverse yaw cases) exhibited very strong lateral accelerations at the cockpit with aileron control inputs. A separate rating scale was devised to isolate these undesirable motion effects from the rating of heading control, per se. This motion rating scale is given below. By using this scale, ride and handling quality problems were separated.

1	OK for normal operations
2	Motions adversely affect piloting task OK for emergency operation only
3	Motions too violent for emergency operation

Both aileron and rudder control power were optimized by the pilots for each configuration.

The pilot rating data for each of the three pilots is summarized in Table D-4. The first number given refers to the usual Cooper-Harper rating and the second number is the motion rating described above. Pilot commentary is summarized in Table D-5.

TABLE D-4

PILOT RATING SUMMARY

Config.	Pilot A	Pilot B	Pilot C	Config.	Pilot A	Pilot B	Pilot C
1A	3, 1*	4, 1.2	2, 1	6A	5, 2	5, 1.5	
1B	1.5, 1			6B	4, 1	3.5, 1.2	
1C	1.0, 1			6C			
1D	1.5, 1	2, 1.5	2.75, 1.5	6D	2, 1	4.5, 1.5	
2A	4, 1	5.5, 1.2	7, 2	7A	7, 1		
2B	3.5, 1	3.5, 1.1	5, 1	7B	5, 1	5, 1	
2C	1.5, 1.5		2.25, 1	7C	3.5, 1	4, 1	
2D	1, 1	3.5, 1.2	2.5 , 1	7D	2, 1	4.5, 1.2	
3A	6, 2	5.5, 1.5	6, 2	8A	6.5, 2		7.25, 2
3B	4, 1		3, 1	8B	5, 1		7, 2
3C	1.5, 1		2, 1	8C			3 5, 1
3D	1.5, 1	2.5, 1.2	3, 1.75	8D	4, 1		3, 1.5
4A	6.5, 2.5		7, 3	9A	3, 1	3.5, 1.2	
4B	3.5, 1		4, 2	9B			
4C	2, 1	3, 1.4	2, 1.5	9C	1.5, 1		1.5, 1
4D	1.5, 1		2.5, 1				
5A	4.5, 1	4.5, 1.2		10A	3, 1		2.75, 2
5B	3, 1	4.5, 1.0		10B	1.5, 1		
5C				10C	2, 1		1.5, 1
5D	2, 1	3.5, 1.0					

*The first rating in each column is the usual Cooper-Harper rating and the second rating is the motion rating.

TABLE D-5

SUMMARY OF PILOT COMMENTARY

<u>Group 1</u>

- Roll-yaw coupling was not a problem in that small sideslip angles resulted from lateral stick inputs (low and high L'_β).
- Rudder coordination, when attempted, was difficult and all three pilots chose to fly with feet on the floor.
- One pilot noticed some minor problems with roll control near the runway for the high L'_β case.
- Undesirable overshoot on turn entry.

<u>Group 2</u>

- Low L'_β cases exhibited considerable adverse yaw; pilots tended to excite undesirable heading oscillations when attempting to coordinate.
- Configurations with higher L'_β could be coordinated with conventional rudder technique.

<u>Group 3</u>

- The low L'_β configuration had considerable proverse yaw which resulted in undesirable heading oscillations and abrupt side acceleration to lateral stick inputs (due to forward pilot location and high angle of attack)
- The higher L'_β configurations tended to have good heading characteristics with feet on the floor.
- Some pilots attempted to use cross control rudders to coordinate the lower L'_β cases. However, it was easy to "slip up" and revert to normal rudder technique which tended to aggravate the proverse yaw problem.

<u>Group 4</u>

- Large complex rudder inputs were required for turn entry and exits making the low L'_β configuration very difficult to coordinate.
- Heading control was very poor for the low L'_β cases due to complicated yawing motions with lateral stick inputs.
- The high L'_β configurations were generally considered as having good lateral characteristics with minor complaints of heading control not being "tight" enough.

Group 5

- Low L'_β configurations required aileron-rudder coordination.
- Rudder required to coordinate was straightforward.
- High L'_β configuration did not require rudder for lateral stick inputs — "two control airplane."

Group 6

- Comments essentially the same as for Group 3.

Group 7

- The low L'_β configurations were flyable but heading control was very poor due to the combined effect of adverse yaw and low frequency response characteristics.
- The long time lag between control input and aircraft response made it very difficult to determine the appropriate control technique, resulting in very large sideslip excursions.
- Significant PIO problems occurred with the high L'_β configuration when control power was not optimized (rudder power too high and roll power too low).

Group 8

- The low L'_β configuration was difficult to coordinate because of low frequency characteristics and required cross-control coordination. Easy to put in wrong rudder which resulted in large sideslip angles.
- The higher L'_β configurations had little roll-yaw coupling and were flown without rudder.
- Proverse yaw seemed unnatural and was confusing to fly.

Group 9

- Pilot comments on use of rudder for the same configuration were generally inconsistent in that the same pilots gave completely different comments on different days.
- Some comments indicated that rudders were necessary for good heading control.
- Other comments indicated that rudder was only required for large lateral stick inputs.

TABLE D-5 (Concluded)

- Still other comments indicated that rudder was not required at all.
- All comments agreed that rudder coordination was simple when required.

Group 10

- Only necessary to use x-control rudder near the ground for low L'_β configuration.
- Had undesirable mid-frequency heading oscillations and jerkiness with low L'_β configuration.
- Higher L'_β configurations were flown with feet on the floor.

The correlation of average pilot rating with ω_{c_ψ} is shown in Fig. D-12. Groups 1-4 should be comparable with data from the first heading control experiment. Comparison of Figs. D-10a and D-12 shows the data from both tests are in agreement. Further examination of Fig. D-12 shows:

- A negligible effect of increasing the dutch roll damping ratio from 0.2 to 0.4 (compare Group 2 with 5 and 3 with 6).
- A negligible effect of lowering dutch roll frequency from 1 to 0.5 rad/sec for the proverse cases (Group 3 and 8 points fall on the same curve) but roughly 1 rating point degradation for the adverse cases (Group 2 versus 7)).
- Roughly a 1 rating point improvement for increasing dutch roll frequency from 1 to 2 rad/sec (Group 2 versus 9 and 3 versus 10).

As a final check on the validity of ω_{c_ψ}, the previously discussed data of Ref. D-1 were reexamined. The proverse and adverse yaw cases were separated and the rating data correlated with ω_{c_ψ}, Fig. D-13. The data roughly follow the same trends established in second heading control experiment but the remaining scatter is not very satisfying.

The preceding clearly indicates that ω_{c_ψ} leaves much to be desired as a handling qualities criterion. There are very strong differences between proverse and adverse yaw cases. There is also an effect of dutch roll frequency. There are several possible explanations. The

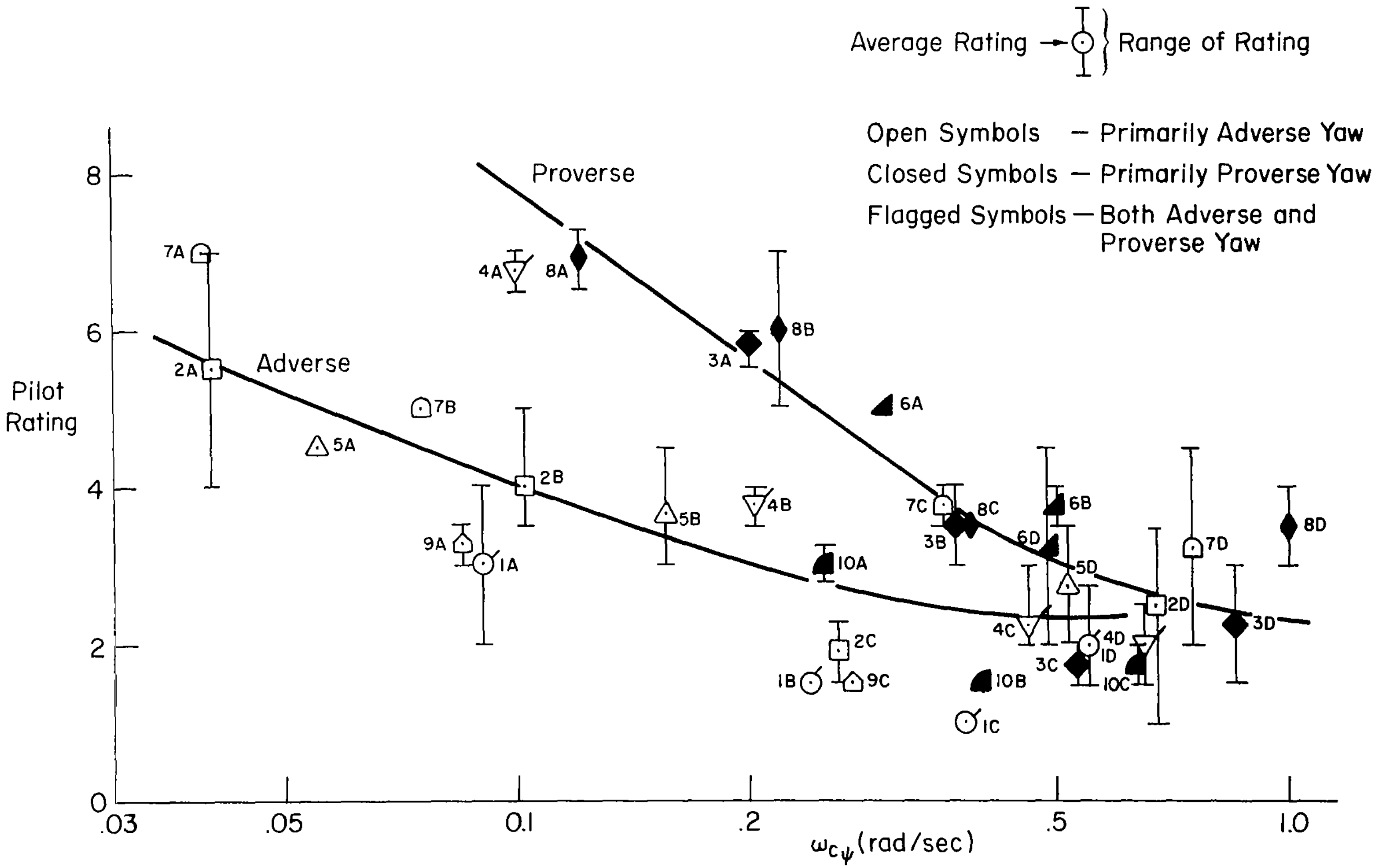


Figure D-12. Average Pilot Ratings vs. Heading Crossover Frequency

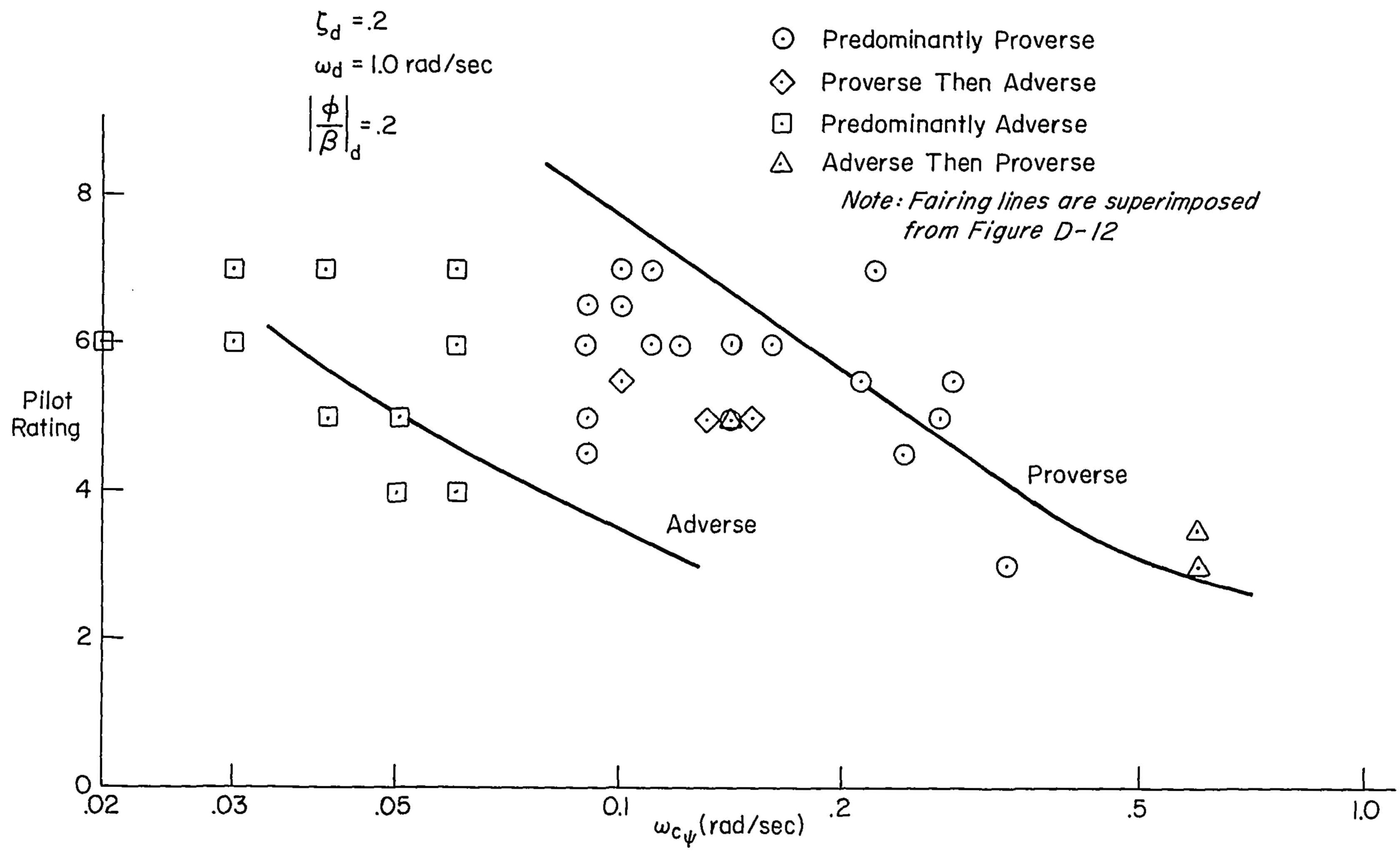


Figure D-13. Reference D-1 Pilot Rating (Pilot B) vs. Heading Crossover Frequency most pessimistic one is that the concept of heading bandwidth as a handling qualities metric is fundamentally wrong. The most optimistic explanation is that the concept is good but the loop closure rules need to be modified. The truth is probably somewhere between the two extremes. The lack of correlation with earlier data is probably due, at least in part, to factors other than heading control (e.g., gust sensitivity and roll control problems) which influenced the pilot ratings.

Late in this project another potential heading control criterion was developed. The remainder of this appendix will describe this criterion and show how it correlates with our own and the earlier data.

The basic idea was that the rudder which would be required to coordinate turns might be <u>indicative</u> of heading control and turn coordination problems. If an aileron-to-rudder crossfeed is used, i.e.,

$$\delta_r = Y_{cf}\delta_a$$

the condition for zero sideslip turns is given by the following ratio of numerators:

$$Y_{cf} = -\frac{N^{\beta}_{\delta_a}}{N^{\beta}_{\delta_r}}$$

For most configurations, $N^{\beta}_{\delta_a}$ and $N^{\beta}_{\delta_r}$ look like first-order polynomials in the frequency range of interest; therefore

$$Y_{cf} \doteq -\frac{N'_{\delta_a}(s + 1/T_{\beta})}{N'_{\delta_r}(s + 1/T_R)}$$

When $|Y_{\delta_a}|$ is small and

$$\left[N'_{\delta_a}L'_p + L'_{\delta_a}\left(\frac{g}{U_o} - N'_p\right)\right]^2 >> \left|\frac{g}{U_o}\, N'_{\delta_a}(N'_{\delta_a}L'_r - L'_{\delta_a}N'_r)\right|$$

the sideslip/aileron zero can be approximated by:

$$\frac{1}{T_\beta} \doteq \frac{1}{T_R} + \frac{N'_p - g/U_o}{N'_{\delta_a}/L'_{\delta_a}}$$

This approximation is given only to demonstrate that the crossfeed parameter is sensitive to $N'_p - g/U_o$ and $N'_{\delta_a}/L'_{\delta_a}$. These two parameters are recognized as the key ones in evaluating turn coordination.

If we define a crossfeed shaping parameter, μ, by:

$$\mu \equiv \frac{T_R}{T_\beta} - 1$$

then the asymptotes of Y_{cf} take on the values shown in Fig. D-14. The rudder sensitivity (N'_{δ_r}) is removed from the crossfeed shaping since it can be separately optimized. Figure D-15 is a summary of the crossfeed shaping required on a plot of the shaping parameter μ versus the ratio of high frequency yawing to rolling acceleration with aileron inputs ($N'_{\delta_a}/L'_{\delta_a}$). Moving vertically on this plot changes the shape of the crossfeed keeping the high frequency gain constant. Moving horizontally produces a change in the crossfeed gain at all frequencies without changing the shape.

An initial correlation of the Ref. D-1 data and that obtained in the two heading control experiments with μ and $N'_{\delta_a}/L'_{\delta_a}$ was excellent except for the low dutch roll frequency cases. These were rated much poorer than the others for similar values of μ and $N'_{\delta_a}/L'_{\delta_a}$. It was found that this effect could be removed by changing from $N'_{\delta_a}/L'_{\delta_a}$ to $N'_{\delta_a}/L'_{\delta_a}\omega_d^2$. In this manner the effects of aileron yaw are reduced roughly proportional to the aircraft directional stability. The ratio of aileron excitation to directional stiffness is a better correlating parameter than aileron excitation alone.

The resulting correlation is shown in Fig. D-16. Both sets of data coalesce very nicely with one exception. Configuration 4A ($\mu = -1.9$ and $N'_{\delta_a}/L'_{\delta_a}\omega_d^2 = 0.3$ in Fig. D-16) was rated worse than the other data would indicate. However, this configuration was given very poor situation ratings (2.5 and 3) because of excessive lateral accelerations due to aileron inputs. Therefore this point was ignored in fairing the curves.

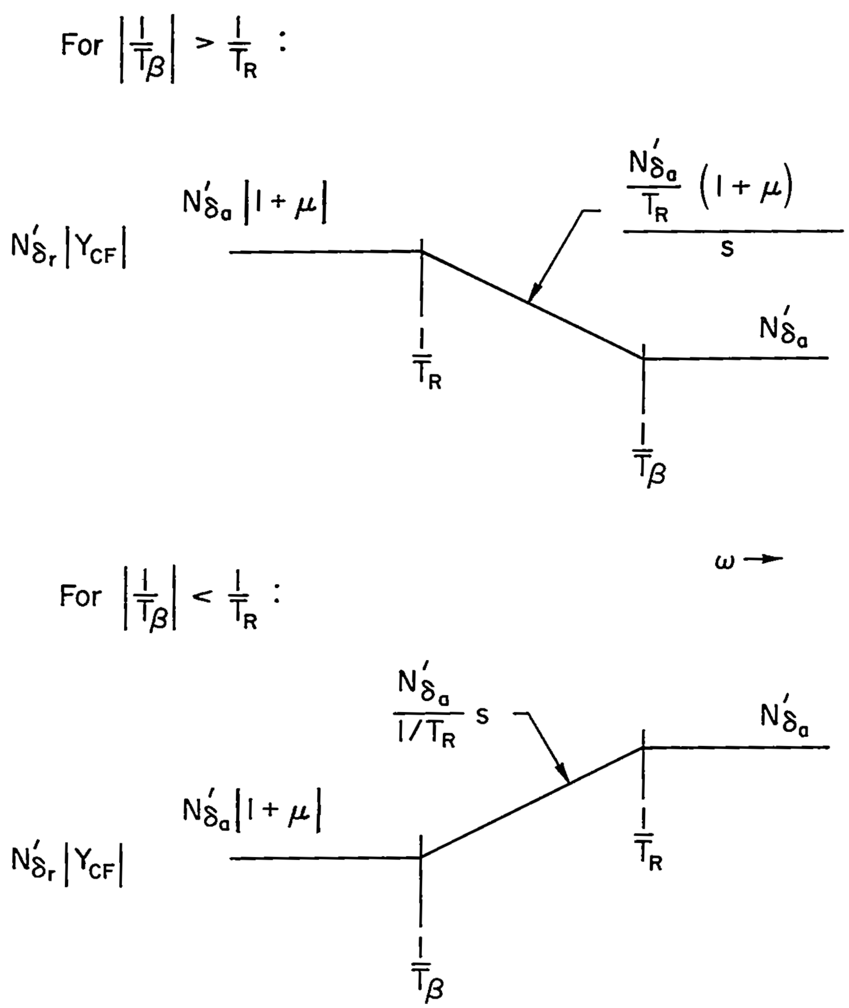
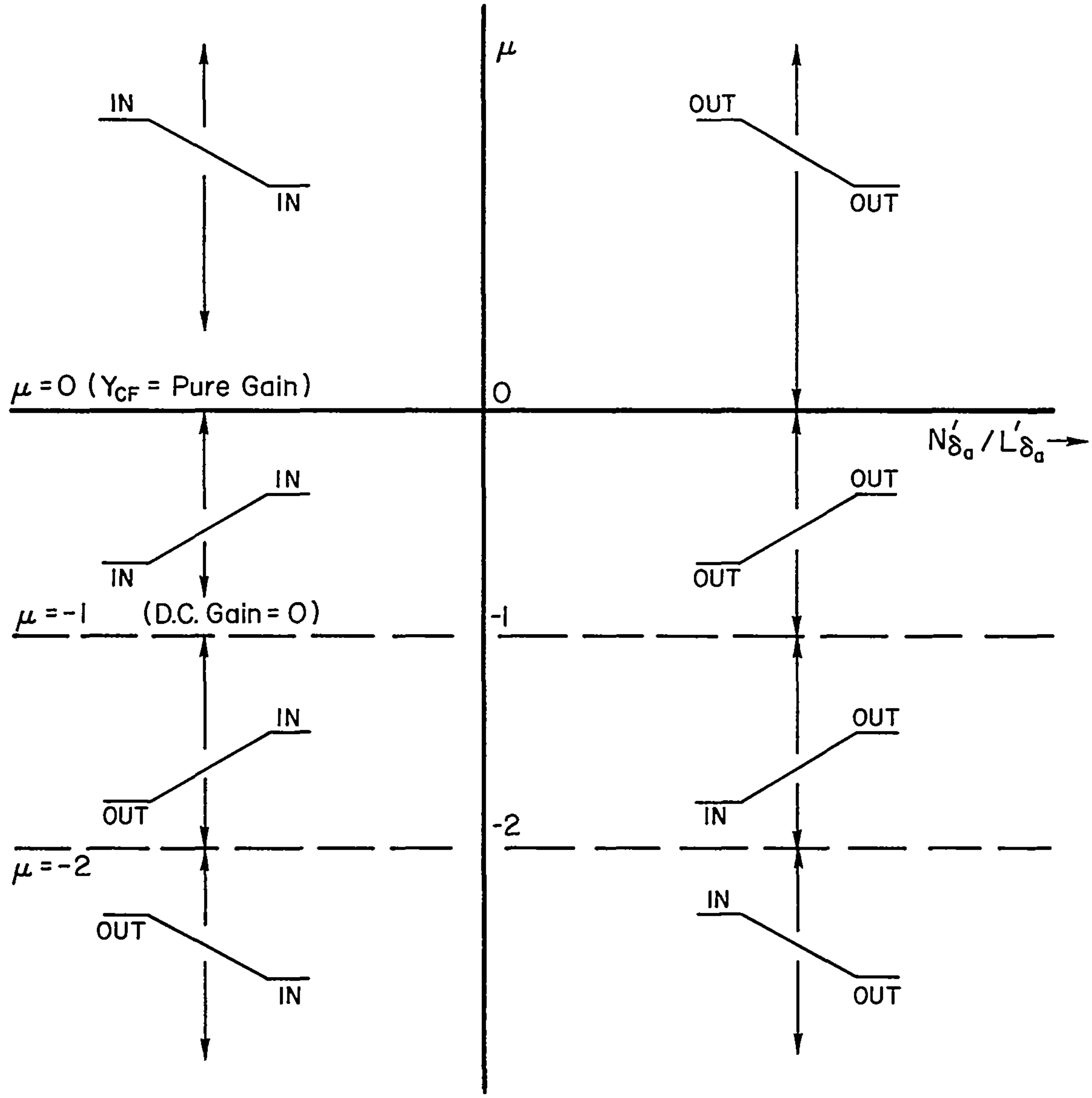


Figure D-14. Asymptotes of Aileron-Rudder Crossfeed



Note: "IN" means rudder into the turn
"OUT" means rudder out of the turn

Figure D-15. Crossfeed Variation with Shaping Parameter

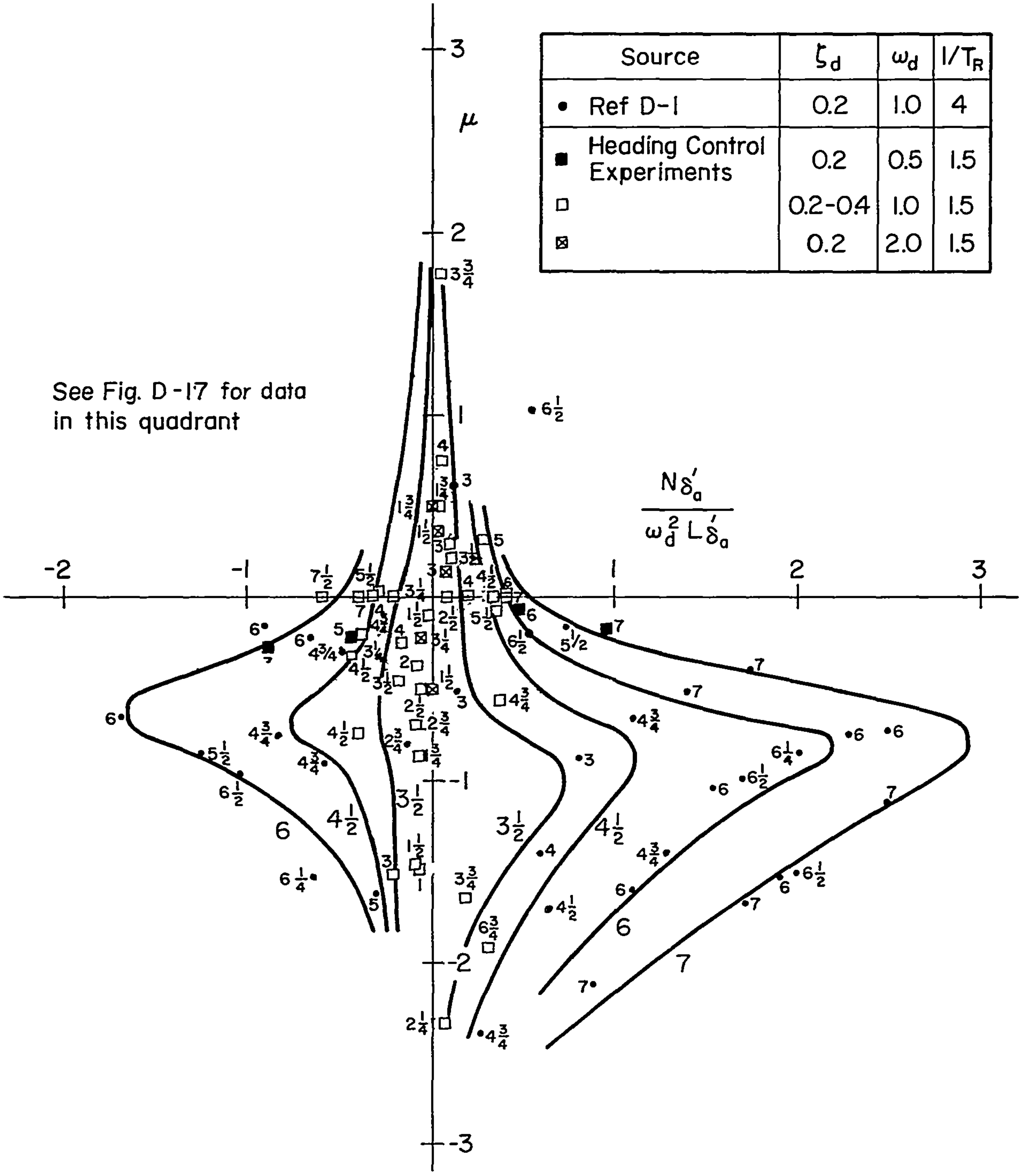


Figure D-16. Rating Correlation with Crossfeed Parameters

The faired curves in Fig. D-16 for positive values of μ and negative values of $N'_{\delta_a}/L'_{\delta_a}$ reflect the Ref. D-6 in-flight data (the simulator data of Ref. D-6 was disregarded because the simulator motion was quite limited and there was more scatter and a rating bias evident in the simulator results). These fairings are shown in more detail in Fig. D-17.

From Figs. D-16 and D-17 the following observations can be made:

- Moderately high proverse (positive) $N'_{\delta_a}/L'_{\delta_a}$ is acceptable in the region where $\mu = -1$. Physically, this corresponds to a sudden initial heading response in the direction of turn followed by decreasing rudder requirement.* (Required dc rudder is zero when $\mu = -1$, see Fig. D-15). It is felt that the pilots are accepting the initial proverse yaw as a heading lead and are not attempting to use cross control rudder to coordinate the turn entry. The allowable values of proverse yaw decrease rapidly as μ becomes greater than −1. Physically this corresponds to an increase in the requirement for low frequency cross control rudder activity (see Fig. D-15) which is highly objectionable. The ratings are less sensitive to μ becoming less than −1 since this represents a requirement for low frequency rudder into the turn which is consistent with normal flying technique.

- The maximum allowable values of adverse $N'_{\delta_a}/L'_{\delta_a}$ occur in the region where μ is slightly greater than −1. This corresponds to decreasing rudder requirements as the turn progresses. As μ becomes greater than −1 the allowable adverse yaw decreases rapidly because of the increase in required dc rudder. The rapid decrease in ratings that occurs when μ becomes less than −1 is due to the rudder reversal required (first rudder into, then out of the turn) during rolling maneuvers. This type of rudder control is virtually impossible to learn and is therefore totally unacceptable.

- Increasing the required rudder-aileron shaping so that $\mu > 1$ (Fig. D-17) results in appreciable reduction in allowable N'_{δ_a}. (The "knee of the curve" is at $\mu \doteq 1$.)

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*Figure D-15 shows that in these cases a washout or lead/lag crossfeed is necessary. The high frequency asymptote is rudder out of the turn so if the pilot does not use the rudder he will initially experience proverse yaw or heading into the turn. As the turn progresses little rudder is required as the low-frequency crossfeed gain is low.

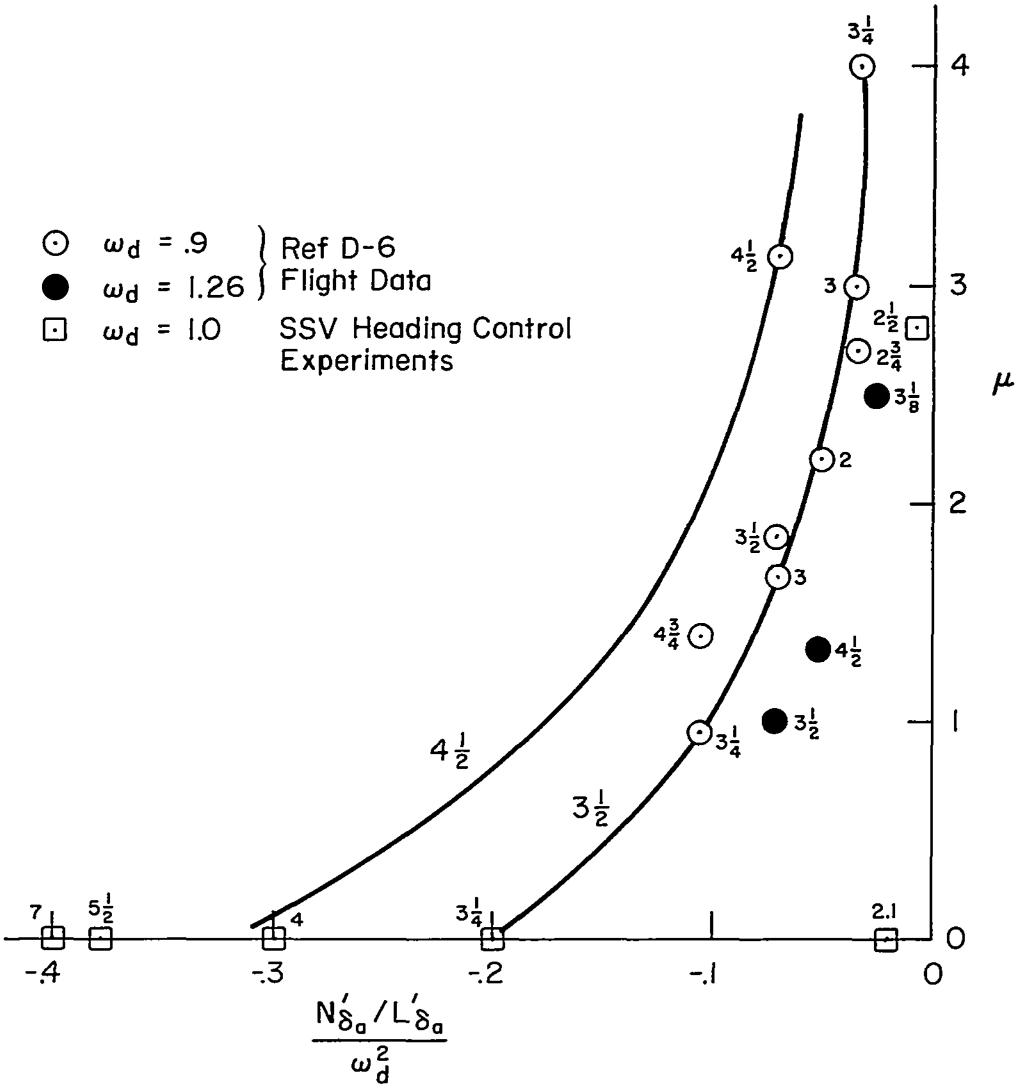
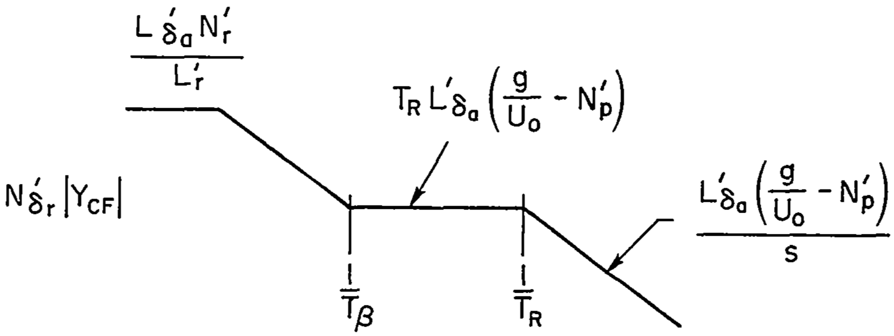


Figure D-17. Pilot Ratings for Positive μ, Negative $N'_{\delta_a}/L'_{\delta_a}$

If the high frequency crossfeed parameter ($N'_{\delta_a}/L'_{\delta_a}$) is very near zero, the required aileron rudder crossfeed takes the form shown in Fig. D-18. The parameter $g/U_o - N'_p$ clearly defines the rudder requirements in this case. Correlation of a few available pilot rating points with $g/U_o - N'_p$ is shown in Fig. D-19. Although the small amount of data does not provide conclusive results, adverse ($g/U_o - N'_p$) should be preferable to proverse. This would be consistent with normal flying technique.



$$\frac{1}{T_\beta} \doteq \frac{-\frac{g}{U_o} N_r}{\left(\frac{g}{U_o} - N'_p\right)}$$

Figure D-18. Required Crossfeed for $N'_{\delta_a} \doteq 0$

The above indicates that the crossfeed shaping parameter has considerable merit as a handling qualities criterion. The results to date are highly encouraging. Additional investigation to further substantiate or refine the criterion seem highly desirable.

	ζ_d	ω_d	$1/T_R$	$\lvert\phi/\beta\rvert_d$
⊙ SST Moving Base Simulation - Ref. D-6 Data	.15	.82 - 1.3	3.5	.45-.59
△ FAA STOL – Ref. D-3 Data	.24-.37	.8 - 1.2	1.2	.24-.36
⊡ SSV Heading Control Experiments	.2 - .4	.5*-2.0	1.5	.4-15.0

* Data points for ω_d = 0.5 are indicated by ⊠

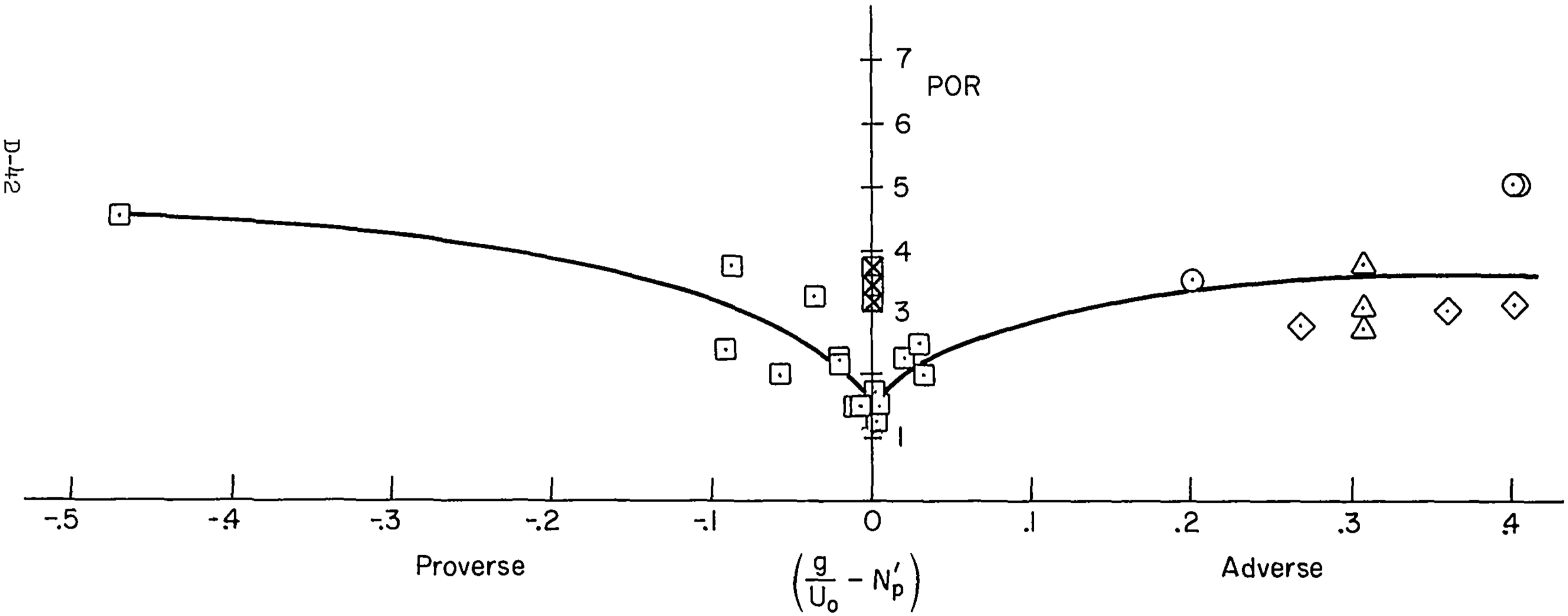


Figure D-19. Pilot Ratings for $|N'_{\delta_a}/L'_{\delta_a}| \le 0.04$

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APPENDIX E

SIMULATION PHYSICAL DESCRIPTION

1. Hybrid Simulation

The simulation experiments of this project were done on the facilities of the NASA Ames Research Center, Moffett Field, California. An Electronics Associates 8400 digital computer was used for the majority of the calculations including integration of the equations of motion, computation of kinematics, and all auxillary calculations such as atmospheric turbulence. Motion drive filters and miscellaneous control system shaping and nonlinearities were done on the analog portion of the hybrid computer. An overall block diagram of the simulation is shown in Figure E-1. Two different simulators were used. All longitudinal experiments and the vehicle evaluations were performed on the S-16 simulator whereas the lateral experiments were done on the FSAA. However, the basic simulation scheme described above and in Figure E-1 applies to both simulators.

2. Side-arm Controller

Since it is expected that the shuttle vehicle will employ a side-arm controller, all of the experiments were performed with this type of manipulator. The controller used is shown in Figure E-2. Elevator trim was via the small wheel which can be seen near the pilot's thumb in Figure E-2. An elevator deflection proportional to the rotation of the wheel was added to that commanded by fore-and-aft motion of the stick. The controller is spring loaded to center both laterally and longitudinally with the force displacement characteristics summarized in Table E-1.

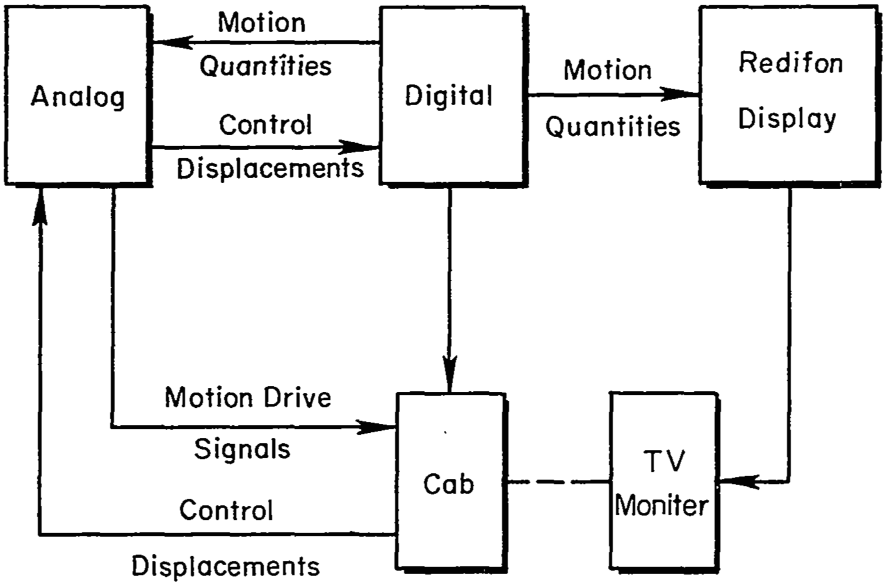

Figure E-1. Block Diagram of Simulation Set-Up

Figure E-2. Side-Arm Controller

TABLE E-1

SIDE-ARM CONTROLLER CHARACTERISTICS

Pitch Axis	Breakout Torque	Back	11.4	in lbs
		Forward	10.0	
	Torque Gradient	Back	0.44	in lb/deg
		Forward	0.50	
	Total Deflection	Back	21	degrees
		Forward	21	
Roll Axis	Breakout Torque	Right	3.24	in lbs
		Left	2.07	
	Torque Gradient	Right	0.14	in lb/deg
		Left	0.15	
	Total Deflection	Right	27	degrees
		Left	27	

3. Redifon Display

The Redifon Display system consists of a TV camera which moves over a fixed visual scene (Fig. E-3) in response to the computed vehicle motions. A summary of the dynamic characteristics of the system is given in Table E-2. Because of the high rates of descent required for the shuttle simulation, a 900:1 scale was used. This increased the maximum vertical rate to 4950 ft/min which was still not enough for some of the test configurations. Further increase in the display scale resulted in noticeable lack of realism in terms of speed cues and runway environment. As a result it was not possible to evaluate some of the longer float time (high rate of descent) trajectories for low L/D vehicles. Since these high rates of descent (up to 24,000 ft/min) would most likely be unacceptable to the pilots, it is felt that the results were not severely compromised by Redifon vertical rate limitations.

Figure E-3. Visual Scene for Redifon Display System

TABLE E-2

DYNAMIC CHARACTERISTICS OF REDIFON DISPLAY SYSTEM

	Displacement	Acceleration	Velocity	Frequency At 30° Phase Lag
Roll	± 100°	4.2 Rad/Sec^2	2 Rad/Sec	1.7 Hz
Pitch	+ 20°, − 30°	16 Rad/Sec^2	3 Rad/Sec	8.5 Hz
Yaw	+ 70°, − 250°	2 Rad/Sec^2	1/3 Rad/Sec	0.8 Hz
Lateral	± 4 1/2 Ft (±.77 Mile*)	.45 Ft/Sec^2 (12.6g*)	0.5 Ft/Sec (267 knots*)	0.42 Hz
Longitudinal	35 Ft (6 Miles*)	.8 Ft/Sec^2 (22g*)	0.53 Ft/Sec (283 knots*)	0.52 Hz
Vertical (Max.)	1 1/4 Ft (1100 Ft*)			
(Min.)	0.17 In. (13 Ft*)	.24 Ft/Sec^2 (6.7g*)	.093 Ft/Sec (5000 Ft/Min*)	0.75 Hz

*At scale of 1:900

4. S-16 Cockpit and Motion System

All vehicle evaluations and longitudinal parameter studies were done on the S-16 Moving Cab Transport Simulator. The motion system consists of three degrees of freedom in roll, pitch, and heave with the dynamic characteristics shown in Table E-3. The cockpit layout including the side-arm

TABLE E-3

DYNAMIC CHARACTERISTICS OF S-16 MOTION SYSTEMS

Motions Generated:	Displacement	Acceleration	Velocity	Frequency at 30° Phase Lag
Roll	± 9°	4.7 Rad/Sec^2	.22 Rad/Sec	0.5 Hz
Pitch	+14°, − 6°	4.7 Rad/Sec^2	.22 Rad/Sec	0.5 Hz
Heave (Vertical)	24 Inches	± 1.0 g (from ambient)	—	0.5 Hz

Drive: Hydraulic Servo (three linear actuators operated differentially or synchronized)

controller and the Sperry EADI is shown in Fig. E-4. Note that airspeed (upper left), altitude (upper right) and heading (bottom) are all displayed on the EADI as well as on conventional instruments. In addition, an expanded altitude display was shown vertically on the right side of the EADI but is not shown in Fig. E-4. The throttle handle on the left was used for speed-brakes when used and the horizontal situation display (lower middle) was not used.

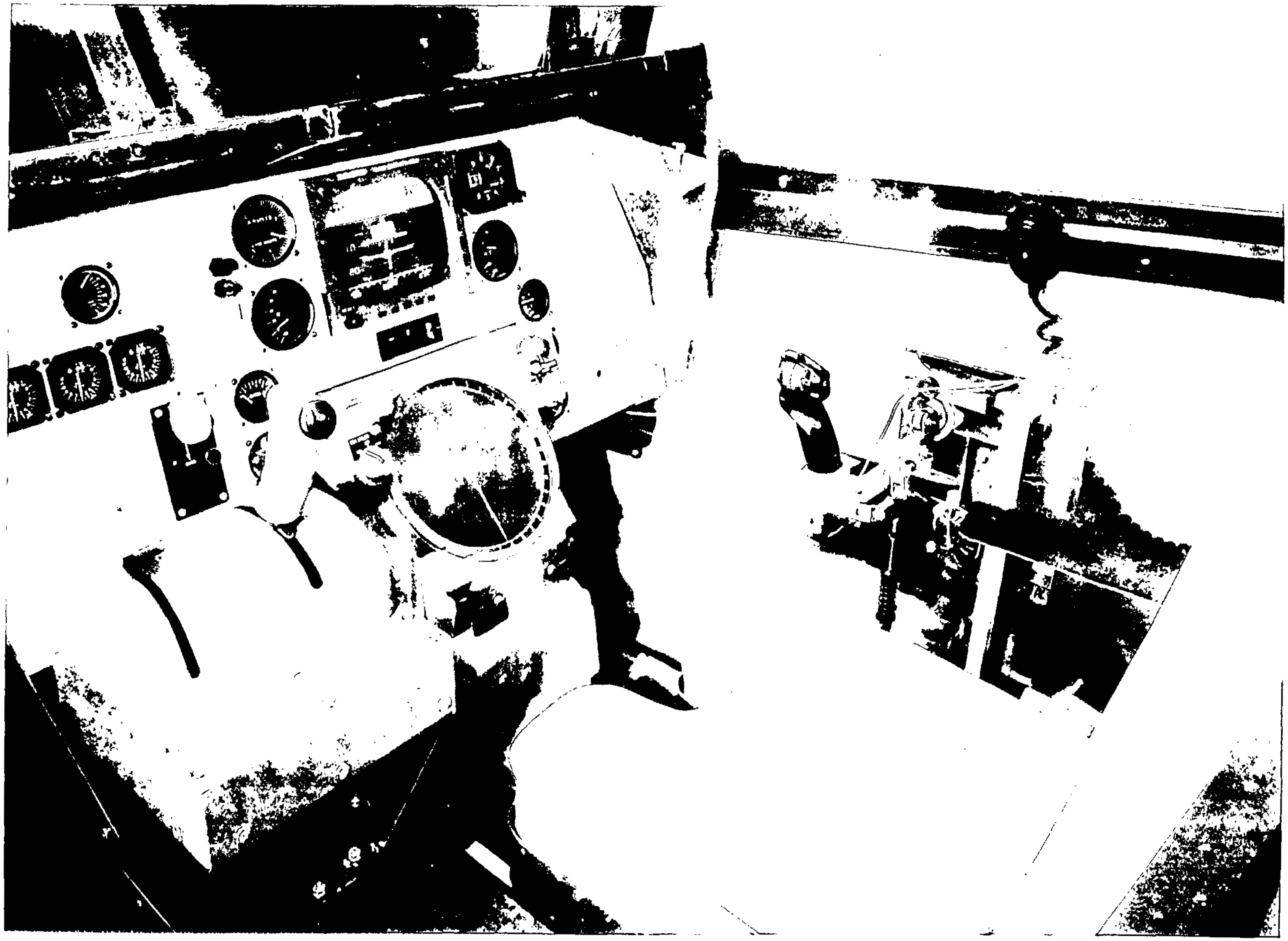

Figure E-4. Cockpit Layout in S16 Simulator

5. Flight Simulator for Advanced Aircraft (FSAA)

This simulator was used in the heading control experiments because of its improved lateral motion characteristics. A summary of the dynamics of the motion system is given in Table E-4. The cockpit layout with the side-arm

TABLE E-4

DYNAMIC CHARACTERISTICS OF THE
FSAA MOTION SYSTEM

Motions Generated:	Displacement	Acceleration	Velocity	Frequency at 30° Phase Lag
Roll	± 45°	4 Rad/Sec²	1.77 Rad/Sec	3.1 Hz
Pitch	± 22 1/2°	2 Rad/Sec²	0.7 Rad/Sec	1.5 Hz
Yaw	± 30°	2 Rad/Sec²	0.7 Rad/Sec	1.7 Hz
Vertical	± 5 Ft	12 Ft/Sec²	8.65 Ft/Sec	2.2 Hz
Longitudinal	± 4 Ft	10 Ft/Sec²	6.32 Ft/Sec	1.8 Hz
Lateral	± 50 Ft	12 Ft/Sec²	17.00 Ft/Sec	1.0 Hz

Drives: Ward-Leonard Electric Servos

controller installed is shown in Fig. E-5.* A slightly different panel layout than that shown was used during the shuttle simulation, the main difference being the addition of a sideslip meter above the airspeed indicator.

6. Turbulence Model

Random turbulence with zero mean wind was simulated for the longitudinal flight path studies and for the vehicle evaluations. The turbulence was simulated by passing the output of a random number generator through the filters shown in Table E-5.

*The center controller (ram's horn) was not used in these tests.

Figure E-5. Cockpit Layout in FSAA Simulator

TABLE E-5

FILTERS FOR RANDOM TURBULENCE

GUST	FILTER
u_g	$G_u = \dfrac{\sigma_u \sqrt{\dfrac{2L_u}{\pi V}}}{1 + \dfrac{L_u}{V} s}$
v_g	$G_v = \sigma_v \sqrt{\dfrac{L_v}{\pi V}} \dfrac{1 + \sqrt{3} \dfrac{L_v}{V} s}{\left[1 + \dfrac{L_v}{V} s\right]^2}$
w_g	$G_w = \sigma_w \sqrt{\dfrac{L_w}{\pi V}} \dfrac{1 + \sqrt{3} \dfrac{L_w}{V} s}{\left[1 + \dfrac{L_w}{V} s\right]^2}$
p_g	$G_p(s) = \dfrac{\sigma_w \sqrt{\dfrac{.8}{L_w V}} \left(\dfrac{\pi L_w}{4b}\right)^{1/6}}{\left[1 + \dfrac{4b}{\pi V} s\right]^2}$
q_g	$G_q(s) = \dfrac{s/V}{\left[1 + \dfrac{4c}{\pi V} s\right]} G_w(s)$
r_g	$G_r(s) = \dfrac{s/V}{\left[1 + \dfrac{3b}{\pi V} s\right]} G_v(s)$

The scale lengths are defined as functions of altitude as follows:

$L_u = L_v = L_w = 1750$ $\quad h > 1750$ ft

$L_u = L_v = 145\ h^{1/3}$ $\quad 100 < h < 1750$ ft

$L_u = L_v = 145\ (100)^{1/3}$ $\quad h < 100$ ft

$L_w = h$ $\quad h < 1750$ ft

The standard deviations are also defined as functions of altitude as follows:

$\sigma_u = 0$	$h > 90{,}000$ ft
$\sigma_u = -27.259 \log_{10} h + 135.046$	$60{,}000 < h < 90{,}000$ ft
$\sigma_u = -.720 \log_{10} h + 8.240$	$100 < h < 60{,}000$ ft
$\sigma_u = 6.8$ ft/sec	$0 < h < 100$ ft

$$\sigma_v = \sigma_u$$

$$\sigma_w = \sqrt{\frac{L_w}{L_u}}\,\sigma_u$$